5-1987

Effect of Shelterbelts on Growth, Yield, and Quality of Alfalfa (Medicago Sativa L.)

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EFFECT OF SHELTERBELTS ON
GROWTH, YIELD, AND QUALITY OF ALFALFA
(MEDICAGO SATIVA L.)

by

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Presented to the Faculty of the

Graduate College in the University of Nebraska

In Partial Fulfillment of Requirements

For the Degree of Master of Science

Major: Forestry, Fisheries, and Wildlife

Under the Supervision of Professor James R. Brandle

Lincoln, Nebraska

May, 1987

EFFECT OF SHELTERBELTS ON GROWTH, YIELD, AND QUALITY OF ALFALFA (*MEDICAGO SATIVA* L.)

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University of Nebraska, 1987

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Crop species differ in their sensitivity to sheltered wind conditions. While studies have indicated significant increases in growth and yield of many crop species sheltered from the wind, little is known about the additional effect of shelter on crop quality which is an important aspect of alfalfa (*Medicago sativa* L.) production.

A field study was conducted in east-central Nebraska during 1984 and 1985 to determine the influence of shelterbelts on alfalfa growth (height, leaf:stem ratio, plant density, stem density, and stems per plant), dry matter yield, and quality (crude protein and *in vitro* dry matter digestibility) under dryland and irrigated conditions. Sheltered plots were harvested at a distance of 7H (H = average height of trees) leeward from a series of shelterbelts, averaging 6 m high and about 70% dense. Alfalfa plots were protected from summertime southerly winds by shelterbelts on the south and west sides. Samples were obtained from four cuttings throughout the growing season and collected at similar maturities for each treatment.

Windspeed was significantly (P<0.05) reduced in sheltered plots for both years with seasonal reductions of 41.0 and 40.3% respectively. Although available soil moisture tended to be consistently greater in shelter for both dryland and irrigated treatments throughout the 1984 and 1985 growing season, moisture levels were not significantly (P<0.10) different for either year. There were no statistically significant (P<0.10) differences between exposed and sheltered treatment means for all growth, yield, and quality parameters measured in either year. While trends in dryland yield showed a 9% increase in the sheltered area during 1984, there were no appreciable trends in growth and quality parameters for either year. No appreciable trends were noted among parameters within the irrigation treatment.

Under these conditions, shelterbelts have no significant effect on alfalfa growth, yield, and quality at a leeward distance of 7H. However, differences between data collected at 7H and visual observations of improved alfalfa growth at closer leeward distances to the shelterbelt warrant further study.

ACKNOWLEDGEMENTS

I would like to thank my major professor, Dr. James R. Brandle for his advice and guidance in this research work. Appreciation is also extended to committee members, Dr. Lowell E. Moser, and Dr. Dennis R. Brink for their guidance and suggestions, and to Mr. Kent M. Eskridge for his statistical expertise.

Thanks are also due the summer help, fellow graduate students, and field technicians who assisted in the many functions of carrying out a research project such as this one.

Most of all, my deepest appreciation is extended to my wife Francine, for her love, support, and patience during my graduate studies.

This research was supported by funds from the McIntire-Stennis Cooperative Research Program.

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INTRODUCTION

In many agricultural regions, field crops are grown in open fields offering no protection from the wind. Winds of excessive force have an adverse effect on crop growth, causing a general decrease in yields (Armbrust et al., 1974; Mitchell et al., 1977; Russell and Grace, 1979a). Windbreaks (any structure which reduces windspeed) and shelterbelts (rows of trees planted for wind protection) can be effective tools for increasing and/or stabilizing crop yields (Rosenberg, 1979). Most of the published data concerning crop production in shelter indicate yield increases of horticultural and field crops by the imposition of shelter (Caborn, 1957; Rosenberg, 1975; van Eimern, et al., 1964). This positive relationship between shelter and crop yields is attributed to a favorable modification of the micro-climate surrounding the crop, resulting in improved water use efficiency by the plant (Marshall, 1967; Rosenberg, 1975; Sturrock, 1975).

Often overlooked in these studies is the mechanical stress wind exerts on plants by the bending, shaking or twisting of plant parts (Jaffe, 1980). Plant physiological processes and plant morphogenesis are altered by this movement causing a reduction in dry weight, leaf area, and height (Armbrust et al., 1974; Grace, 1977). Plant tissue composition is affected as well, however, the effects on crop quality are not clearly understood (Barker et al., 1985; Greig et al., 1974; Mitchell et al., 1977;).

Field crops harvested for their above ground biomass, such as alfalfa, can be greatly influenced by mechanical wind stress. Alteration of forage growth and plant structure by wind stress may affect quality as well as yield of the crop harvested. Any reduction in wind velocity by shelter reduces the influence of mechanical wind stress on plants as well as favorably modifying the surrounding microclimate. The degree to which this reduction affects forage yield and quality needs further clarification.

Research was undertaken to determine the effect of wind protection by shelterbelts on growth, yield, and quality of alfalfa (*Medicago sativa* L.) forage. Specific parameters measured were height, leaf:stem ratio, plant density, stem density, stems per plant, dry matter yield, crude protein (leaf, stem, and whole plant), and *in vitro* dry matter digestibility (leaf, stem, and whole plant).Measurements were taken under both irrigated and dryland moisture regimes in order to determine the influence of irrigation on shelter effects.

LITERATURE REVIEW

MICROCLIMATE IN SHELTER

Many studies have been conducted to determine the influence of windbreaks on crop growth. Comprehensive reviews are given by Jensen of Denmark (1954) and Caborn in Scotland (1957). United Nations agencies have sponsored extensive reviews of windbreak research (van der Linde, 1962 for FAO and van Eimern et al., 1964 for WMO). Stoeckler (1962), Read (1964), Marshall (1967), Rosenberg (1975), and Sturrock (1984) have also contributed additional reviews with emphasis on the mechanisms of windbreak effects on microclimate and plant growth. Emphasis in this review will be on microclimatic factors measured in this study (wind velocity, air temperature, and soil moisture), mechanical wind stress, and the relationship of these factors to crop growth, yield, and quality.

Wind Velocity

The primary function of a windbreak is to modify local wind movement in the sheltered zone. This causes changes in the microclimate that are conducive to improved plant growth and yield (Woodruff et al., 1959). Windbreaks of proper design cause significant reduction of wind velocity for distances of 15 to 20 times the height of the windbreak to the leeward and for distances of 2 to 5 times the height of the windbreak to the windward (Caborn 1957; 1960). Height, length, and density are the chief determinants of the degree of shelter and of the size and shape of the sheltered zone (Caborn, 1957).

The extent to which shelter is provided beyond a barrier is proportional to its height. The higher the barrier, the greater will be the distance of its downwind as well as upwind influence. Variations do occur depending on the stability of the atmosphere, on the speed of the approaching wind, and on the roughness of the ground or crop surface (Marshall, 1967). Unstable atmospheric conditions affect the extent of shelter downwind by causing windspeed recovery to occur faster in the lee of a windbreak. Slower approaching windspeeds along with increased surface or crop roughness improves the effectiveness of a windbreak, causing greater windspeed reductions over the entire leeward region (McNaughton, 1987). Barrier height (H) is commonly used in shelter research to express results obtained at various distances from the windbreak.

Windspeed reduction patterns are primarily determined by barrier density. Dense windbreaks with little porosity deflect most of the approaching air currents over the top of the barrier creating turbulence. Lower air pressure on the leeward side causes the rapid return of this turbulent air to the ground surface, decreasing the extent of the sheltered area (Sturrock, 1975). Porous barriers permit penetration of the wind and prevent the rapid return of air, which has over topped the windbreak, to the ground near by. Porous barriers reduce windspeed near the windbreak less than dense barriers but the extent of downwind protection is greater. For example, a dense windbreak (density 70%) can protect an area up to 10-15H downwind. By increasing porosity to about 50%, the downwind influence can be increased to 20-25H (Rosenberg, 1975). Based on field and wind tunnel studies, optimum protection for vegetation is provided by a windbreak with a moderate permeability of 40 to 50% (Caborn, 1957; Marshall, 1967).

The longer the windbreak the more constant its influence. Windbreaks of sufficient length effectively reduce oblique winds, provided the deviation of the wind from the perpendicular is not too great. They also protect more land and reduce to a minimum the jetting effects of wind blowing around the ends (Sturrock, 1975). Even for small fields, the length of the windbreak should not be less than twenty times the tree height in order to achieve maximum efficiency (Collins, 1962).

Many studies have been made on the variation of crop yield with distance from shelterbelts. There is general agreement that micrometeorological factors significantly affecting crop yield are limited to within 8-12H of the barrier (Marshall, 1967; van der Linde, 1962; van Eimern, 1964). Usually only windspeed shows detectable variation from unsheltered control values beyond 15H (Marshall, 1967).

Air Temperature

Windbreaks influence air temperature patterns through reduction in turbulent air mixing. When turbulent exchange is restricted, aerial diffusion of sensible heat generated at the plant/soil surface decreases and temperature gradients are intensified. The result is higher daytime air temperatures in shelter (Rosenberg, 1979). Temperature increases during the day within 10H of the lee are generally less than 2^{o}C although higher increases of 4^{o}C have been reported (Marshall, 1967; Woodruff et al., 1959). At greater distances from the windbreak, porosity, high soil moisture, cloudiness, and low net radiation all tend to reduce the daytime air temperature differences between sheltered and exposed fields (Marshall, 1967; Skidmore and Hagen, 1970).

At night, plant and soil surfaces become the sink rather than the source of heat and temperature inversions develop unless winds mix the inversion layers. The reduction of turbulence in shelter causes temperature inversions to intensify resulting in lower night temperatures in shelter (Rosenberg, 1979). The greatest daily amplitude of air temperature in shelter occurs where windspeed is reduced the most and may influence physiological and morphological processes (Bates, 1911).

Soil Moisture

Soil moisture conservation and redistribution is a major influence of windbreaks on plant growth, particularly under dryland conditions (Rosenberg, 1967). Shelter influences soil moisture levels by two processes; evapotranspiration and snow accumulation or distribution (Skidmore, 1969). Wind causes aerial diffusion of sensible heat and water vapor which results in evaporation. Reduction of evaporation by shelter is proportional to the decreases in windspeed provided turbulence is not excessive (Skidmore, 1969; Skidmore and Hagen, 1970). Dense windbreaks are less effective in reducing evaporation than permeable windbreaks because excessive turbulence transports water vapor rapidly away from the sheltered zone promoting further evaporation (Bodrov, 1936; van Eimern, 1966).

By reducing windspeed in shelter, the direct evaporation of moisture from the soil is reduced, resulting in significant moisture savings. This temporary moisture savings coupled with a favorable microclimate bring forth larger plants transpiring more water from the soil. Given a long enough period of time, the soils in shelter and in exposed areas will eventually reach the same degree of dryness (Rosenberg, 1975). Under dryland conditions and inadequate rainfall, sheltered plants could use more soil water and experience greater water stress than exposed plants (Frank et al., 1974; Grace, 1987).

Evapotranspiration can be greater in shelter because of reduced stomatal resistance allowing soil water use to exceed levels maintained in the open. Under non-advective conditions of sensible heat, differences in evapotranspiration between shelter and exposed areas have been shown to be small, however, under advective conditions evapotranspiration rates are higher in the exposed areas resulting in greater water savings for the sheltered zone (Brown and Rosenberg, 1971; Miller et al., 1973).

In northern latitudes, windbreaks will aid in the uniform distribution of snow, thereby improving the potential supply of moisture to spring grown crops. Density of field windbreaks affects the quantity of snow trapped and its distribution. A dense windbreak generally traps snow immediately adjacent to the windbreak, whereas less dense windbreaks will distribute snow further into the crop area and provide a greater potential for increasing soil water levels from snow accumulation (Frank and Willis, 1978; George, 1971; Siddoway, 1970).

Humidity

The humidity regime leeward of a windbreak is not always straight forward due to many microclimatic factors. While air temperatures tend to be greater, water vapor generated by transpiration and evaporation is not readily transported away from the evaporating surface in shelter and as a result, absolute humidity remains high except during periods of dew formation (Rosenberg, 1975; Sturrock, 1975). As a consequence relative humidity is generally greater in shelter even during the daytime regardless of higher temperatures. At night relative humidity in shelter is greater because of lower air temperatures (Read, 1964; Rosenberg, 1975). Numerous studies have shown a 2 to 3% increase in relative humidity and a 0.67 to 1.3 mb increase in absolute humidity in shelter (Caborn, 1957). Under irrigated shelter conditions, a 4 to 5 mb increase in absolute humidity has been reported (Rosenberg, 1966b).

Soil Temperature

Soil temperature has been observed to be higher in shelter (Marshall, 1967; van Eimern et al., 1964). Increases were greatest when the soil was bare and dry, and least when the soil surface was moist or the sky was cloudy (Casperson, 1957; Steubing, 1954). Soil temperatures in shelter are usually elevated during the day and slightly depressed at night (Rosenberg, 1966b). Midday soil temperature increases up to 2.5^{o}C at a 20 cm depth have been reported (Jensen, 1954).

Radiation Balance

The radiation balance is not changed significantly by shelter, except near the windbreak itself (Marshall, 1967;

Rosenberg, 1967; van Eimern et al., 1964). Windbreaks may intercept, reflect, and reradiate some solar or terrestial radiation. Depending on the windbreak orientation, it may reflect solar radiation from one side and shade an area on the other side (Skidmore, 1976). Shading may be unimportant since long shadows are cast only when the sun is low and solar radiation is low (Rosenberg, 1967).

CO_2 Concentration

Shelter influences CO_2 concentration within the crop canopy by reduction of windspeed and air temperature. At low windspeeds, photosynthetic rate in the field may be decreased because of CO_2 shortages in the air surrounding the leaves (Lemon, 1970). During the daytime, reductions in turbulent air mixing in shelter resulted in decreases of 1 ppm CO_2 or less in the zone directly above a crop canopy. This small decrease in CO_2 concentration was considered to have a negligible effect on crop photosynthesis. It is proposed that although turbulent air mixing is reduced in shelter, atmospheric mixing above the sheltered field is sufficiently strong, except in the most calm conditions, to prevent any daytime reduction in CO_2 concentration from significantly reducing photosynthetic rate (Brown and Rosenberg, 1972).

Night time CO_2 concentrations have been observed to be as much as 3.5 ppm greater in shelter (Brown and Rosenberg, 1972). Because of nocturnal temperature inversion, atmospheric stability is strong and under these conditions, CO_2 liberation by respiring plants accumulates over and within the crop canopy. However, at sunrise, higher CO_2 concentrations in shelter would cause an insignificant increase in the photosynthetic rate (Brown and Rosenberg, 1972; Rosenberg, 1975).

CROP RESPONSE TO SHELTER

Physiological Response

Crop physiological responses to shelter are conducive to greater dry matter production under the reduced evaporative demand conditions of shelter (Rosenberg, 1975). Greater dry matter production can result from higher rates of photosynthesis, lower rates of respiration and/or photorespiration or a combination of these.

Reduced evapotranspiration affects rates of photosynthesis by reducing moisture stress on photosynthesizing leaves (Skidmore, 1969). As a result, there is less stomatal resistance to diffusion of water vapor and CO_2. The stomates remain more widely open and the duration of photosynthetic activity is longer. This greater photosynthetic opportunity coupled with reduced evapotranspiration accounts for the increased water use efficiency and dry matter production found in shelter (Rosenberg, 1975; Skidmore and Hagen, 1970).

Sheltered plants may transpire more water than unsheltered plants when exposed to strong evaporative demand. Unprotected plants may exhibit incipient wilting with large increases in stomatal resistance. Lower stomatal resistance in shelter causes more transpiration, however, the opportunity for photosynthesis remains greater (Rosenberg, 1975).

Stomatal resistance undergoes considerable variation during the day in both sheltered and exposed plants. Plants encounter temporary stress periods when roots are unable to supply water as rapidly as it is evaporated from the leaves. Stomates will close partially until internal plant water deficits are relieved. Differences in stomatal resistance between sheltered and exposed plants increase when soil moisture content decreases (Brown and Rosenberg, 1970). Moisture stress in shelter is less severe at low soil moisture levels due to lower evapotranspiration (Rosenberg, 1975).

Growth and Development

Significant growth advantages have been reported for plants sheltered from the wind. Greater leaf area index, plant height, and dry matter production have been associated with sheltered wheat [*Triticum aestivum* (L.) L.] (Aase and Siddoway, 1974; Skidmore et al., 1974; Skidmore et al., 1975), soybeans [*Glycine max* (L.) Merr.] (Ogbuehi and Brandle, 1981; Radke and Burrows, 1970; Radke and Hagstrom, 1974), corn (Zea mays L.) (Shah, 1962), sugar beets (Beta vulgaris L.) (Brown and Rosenberg, 1970; Marshall, 1974), dry beans (Phaseolus vulgaris L.) (Rosenberg, 1966a), and cotton (Gossypium hirsutum L.) (Barker et al., 1985). Ogbuehi and Brandle (1981) reported that improved soybean growth in shelter was related to higher leaf area index, net assimilation rate, relative leaf growth rate, and crop growth rate during the growing season. Treatment differences in soybean performance were related to differences in plant water stress and canopy light climate after canopy closure. Deeper penetration of light into the canopy was observed in the sheltered crop. Exposed plants were shorter and had a significantly greater leaf area density in the uppermost 20% of the canopy which imposed greater restriction on radiation penetration to the layers beneath.

Increased soil and air temperature contribute to improved germination and early growth in shelter, but it is difficult to isolate these parameters and ascertain their precise effects (Sturrock, 1975). Higher temperatures within sheltered areas frequently lead to earlier or successful maturation of crops. Earlier maturity may be important to the economics of growing, even when there is no increase in yield (Sturrock, 1984). Higher temperatures also promote earlier spring production and prolong growth in autumn, thus extending the growing season of perennial crops when unsheltered temperatures are below the threshold for growth

(Marshall, 1967). In some cases, the benefits of shelter may be offset by higher than optimal temperatures for photosynthesis in some sheltered plants, especially those with C_3 photosynthetic pathways (Grace, 1977).

Crop Yield

Although the effect of windbreaks on microclimate is varied and complicated, it is usually beneficial to plant growth, especially in areas of strong wind or where snow moisture is an important factor (Chang, 1968). Over-all windbreak effects on crop yield vary according to climate (Marshall, 1974), season (Sturrock, 1975; van Eimern, 1964), available soil moisture (Alcock et al., 1976; Marshall, 1974), soil type (Stoeckler, 1962), culture (Sturrock, 1975), crop variety (Rosenberg et al.,1967; Sturrock, 1970), and crop species (Andersen, 1943; van Eimern, 1964).

Yield increases in the presence of shelter are greater in continental than in oceanic climates due to the drier summers of the former (Marshall, 1967). On a seasonal basis, percentage yield responses in dry years tend to be greater than in wet years (Rosenberg, 1975; Sturrock, 1975;). Increases due to shelter in dry years are due to soil moisture being a limiting factor for crop growth, so any means whereby moisture is conserved is beneficial. In the northern regions of the Great Plains, soil moisture from snow accumulation proved to have a greater affect on yield than microclimate modification during the summer (Frank et al., 1974; George, 1971). If adequate rainfall is not distributed throughout the season and assuming transpiration is a function of greater leaf area in shelter, water depletion will result and induce soil moisture stress in shelter (Chang, 1968; Rosenberg, 1975).

Weather changes during the growing season influence the microclimate in shelter. Yield response may thus be affected depending on time of harvest and vary throughout the season if more than one harvest is obtained (Alcock et al., 1976; Marshall, 1974).

Response to shelter has been shown to vary with soil type. Percentage yield increases due to shelter may be greater on less fertile sites (Stoeckler, 1962; Trenk, 1948). Indications are that percentage yield increases on lighter, free-draining, sandy soils exceed those on heavy, clay-rich soils in the same climate (Andersen, 1943).

Very large responses to shelter from crops grown in Russia have been reported. In contrast, crop responses in the American Great Plains, have not been as dramatic. This difference in yield response is ascribed to breeding programs that have improved drought tolerance and disease resistance of American crop cultivars (Sturrock, 1975). Crop cultivars respond differently to shelter with large yield differences being reported for cultivars of snap beans

(*Phaseolus vulgaris* L.) (Rosenberg et al., 1967) and soybeans (Sturrock, 1970). These differences may arise because of variation in cultivar adaptability to the macro-climate of the area in which the crop was grown (Rosenberg et al., 1967).

Crop species response to shelter can be classified into three groups: low, medium, and high. Among the crops of low response to wind protection are the drought-hardy small grains. Moderately responsive are rice (*Oryza sativa* L.) and forage crops such as alfalfa, clover (*Trifolium spp.*), and grasses. Among the crops most responsive to shelterbelt protection are horticultural crops, fruits, and other tender crops such as tobacco (*Nicotiana tabacum* L.) and tea (*Thea sinenis* L.) (Stoeckler, 1965).

Most of the yield comparisons between sheltered and wind exposed crops have been with grain and horticultural crops. Fewer studies have been reported for forage crops consisting of grasses, legumes, or mixtures of both.

In Denmark, shelter improved first year ryegrass (*Lolium spp.*) -redclover (*Trifolium pratense* L.) growth by 20% (Jensen, 1954). In Germany, shelter increased grass pasture yields by 6 to 14% over 6 years (Batjer et al., 1967). Russell and Grace (1979b) compared growth of tall fescue (*Festuca arundinacea* Schreb.) and perennial ryegrass (*Lolium perenne* L.) under sheltered and exposed conditions for 3 years in Scotland. Shelter did not affect spring growth but subsequent regrowth after harvest was increased by up to 28%. Grass and alfalfa yields at one site in Hungary were increased by 15.3% and 22% respectively within a sheltered zone of 3 to 10H (Gal et al., 1963). In other areas, sheltered grass pastures produced 33% of normal spring yield in a dry season, whereas on exposed fields most of the grass became withered (Benkovits, 1955). Alfalfa yields were increased from 50 to 100% when protected by shelterbelts in Argentina, where the drying winds of the region can influence yields dramatically (Cittadini, 1955).

In Russia, Gorshenin et al. (1934) indicated that expected crop increases on land between shelterbelts is 100% for smooth bromegrass (Bromus inermis Leyss.) and 203% for alfalfa. The excellent response of forage crops to shelterbelt protection was also cited by Ignatiev (1940) for alfalfa and crested wheatgrass [Agropyron cristatum (L.) Gaertn.] where yields were on occasion increased by 200%. Shaposhnikov (1946) found yields of clover hay increased by 39%.

In the central Great Plains of the U.S., alfalfa yields were 60 to 70% more in the best part of a protected field as compared to an overall field average (Bates, 1944). Mixed alfalfa, timothy (Phleum pratense L.), and red clover hay yielded 37% more in the 1 to 7H leeward zone than the normal field average on sandy soils in Wisconsin (Trenk, 1948). In Wyoming, crested wheatgrass yield at 0 to 2H leeward (south) was double the yield at 9H leeward (Quayle, 1941).

Crop Quality

Studies have shown that plants protected from the wind may undergo changes in chemical composition. The effect of shelter on pasture quality was examined in Hungary where shelter improved the total weight, dry weight, vitamin C, digestible protein, and starch of pastures by 9, 68, 108, 144, and 85% respectively over values for unprotected pastures (Benkovits, 1955). However in the U.S., a study over 3 growing seasons found that herbage growing on the edges of a nearby forested area were lower in N-free extract and had more crude fiber, calcium, and phosphorous than plants in the open meadow (McEwen and Dietz, 1965). In Holland, grasses within a 20 m strip adjacent to a popular shelterbelt contained more raw cellulose and less protein and carbohydrates than adjoining pastures (Radcliffe, 1983). Elsewhere, crude protein and crude fiber in pastures were found to be unaffected by tree windbreaks (Altena, 1955).

In Saudi Arabia, the yield of oat (*Avena sativa* L.) forage grown under sheltered and irrigated conditions was unaffected, however crude protein and ash content were increased by 14 and 16% respectively, while crude fiber content was slightly lower (1%). In the same study, sheltered barley (*Hordeum vulgare* L.) forage yields were also unaffected with higher crude protein and ash contents of 30 and 13%, and slightly lower crude fiber contents (1.5%) (Younie and Ruxton, 1977).

Irrigated Crops

In conditions of high evaporative demand (a function of radiation, vapor pressure deficit, and wind), irrigation by itself can only partially relieve plant moisture stress, even in plants well furnished with water (Miller et al., 1973; Sturrock, 1984). Under these conditions leaf water potential falls, when it reaches a critical value, depending on species and variety, the stomata close to reduce transpiration and relieve plant stress. Although full turgidity will be regained after darkness, the close coupling of photosynthesis and transpiration reduces photosynthetic opportunity and hence growth potential (Sturrock, 1984). Fluctuations in the evaporative demand of the atmosphere affect cell enlargement and differentiation before reduction of photosynthesis (Hsiao, 1973). By reducing wind and vapor pressure deficit, shelter alleviates some of the evaporative demand, maintains a higher leaf water potential, and allows irrigation water to be used more effectively (Miller et al., 1973; Sturrock, 1984). Increased yield is associated with increased water uptake, although shelter improves the efficiency of its use (Reddy and Kulkarnie, 1978; Rosenberg, 1966a).

Under continued dry conditions, shelter alone may not benefit plants throughout the growing season. This is especially true when plant root systems are small or restricted or when the soil has a low storage capacity (Sturrock, 1975). Increased stimulation of vegetative growth early in the growing season by shelter can be detrimental if soil water is inadequate to prevent later development of high plant water stress (Frank et al., 1977b; Rosenberg, 1967; Skidmore et al., 1975). However, supplementary water can reinforce the earlier shelter effect and prevent yield reduction (Sturrock, 1984).

Experiments conducted in North Dakota indicated a significant increase in growth and yield of spring wheat and soybeans when grown with a combination of shelter and irrigation (Frank et al., 1974; Frank et al., 1977a; Frank et al., 1977b). This treatment resulted in the most favorable plant water status, with higher leaf water potential and lower stomatal resistance. Over two years, wheat yield with shelter and irrigation averaged 21.8% more than irrigation in the open; the corresponding yield increase for soybeans averaged 22.5%.

Irrigated forages grown in Saudi Arabia, yielded more when shelter from date palm (*Phoenix dactylifera* Linn.) windbreaks was provided. During the summer and early winter months, alfalfa yielded 21% more and rhodesgrass (*Chloris gayana* Kunth) yielded 12.4% more than in the open

(Farnworth, 1974). During the winter months in the same location, the response to shelter of irrigated oats and barley forage was shown to be poor. The data suggested that a reduction in evapotransporation in warmer months is the greatest advantage to be gained from the use of windbreaks (Younie and Ruxton, 1977).

MECHANICAL WIND DAMAGE

Windbreaks reduce windspeed to protect crops from physical damage caused by wind or wind-blown soil. The most frequently observed form of mechanical wind damage is the lodging of cereal grains, accompanied with seedhead breakage and seed shatter close to harvest (Sturrock, 1984). Many times in sheltered areas, crop plants are taller making them more susceptible to lodging, whereas in exposed areas, reduced stem length and increased stem strength produce plants more resistant to lodging. Reduced windspeed in shelter protects crops from lodging but excessive turbulence behind dense barriers may increase it (Marshall, 1967).

Physiological as well as physical wind damage can occur from the tearing, bruising and abrading of plant leaves and stems. Wilson (1984) exposed Acer pseudoplatanus trees to windspeeds of 3.5 m/s in a wind tunnel and reported light and dark brown foliar lesions and leaf deformities occuring as a result of abrasive contact. This damage included rupture of adaxial and abaxial epidermal cells, collapse of the mesophyll, cracking of the cuticle, and smoothing and redistribution of wax deposits on the leaf surface. Similar damage in strawberry (*Fragaria x ananassa* L.) leaves was noted by Mackerron (1976). He proposed that such damage may affect the physiological capacity of the leaf both in terms of CO_2 assimilation and control of water loss.

Grace (1974) found increased transpiration rates in tall fescue during exposure to high wind speeds and suggested that this effect may be a consequence of mechanical damage to the leaf surface. Other studies by Grace and his colleagues, showed growth rate reductions by tall fescue over a range of windspeeds (1 to 7 m/s), the extent of the reduction being dependent upon water and nutrient regimes (Grace and Russell, 1982; Pitcairn and Grace, 1982). In all cases, plants exposed to wind treatments displayed higher surface conductances and transpiration rates (Grace, 1974; Grace and Russell, 1977; Grace and Russell, 1982; Pitcairn and Grace, 1982). The higher surface conductances were associated with abraded and polished leaf surfaces (Thompson, 1974), and macroscopic damage to the leaf margins and tips (Russell and Grace, 1978). In many cases, high transpiration rates were demonstrated to be associated with reductions in tissue water content or water potential (Grace, 1974; Grace and Russell, 1982; Pitcairn and Grace, 1982). Declines in water potential resulted in reductions of growth rate (Grace and Russell, 1982).

Macroscopic features of plant damage are evident when wind carries particles of soil and sand. Crop damage may occur even when soil losses are below the rates considered damaging to the soil (Kimberlin et al., 1977). Fryrear and Downes (1975) showed that erosion damage to seedling crops is proportional to the duration of exposure and to the magnitude of the eroding soil flux. Wind erosion damage in laboratory wind tunnels reduced plant seedling survival, growth rate, and height of grain sorghum (*Sorghum bicolor* L.) (Armbrust, 1982), winter wheat (Armbrust et al., 1974), alfalfa (Lyles and Woodruff, 1960), and tomato (*Lycopersicum esculententum* Mill.) (Greig et al., 1974) to name a few. Reduced growth of sandblasted crops appears to be a combination of reduced leaf area and physiological changes; mainly from decreased photosynthesis and increased respiration (Armbrust, 1982).

MECHANICAL WIND STRESS

The beneficial effects of shelter on crop growth can be mediated in ways other than microclimate modification. Another important aspect of wind protection includes minimizing the direct influence of wind on plant morphology (Mackerron, 1976). Morphological differences between wind exposed and wind sheltered plants occur because plants are sensitive to mechanical wind stress. Plants become wind stressed by the bending, flexing, shaking, and twisting of their anatomy. Both physiological processes and morphogenesis are altered by this movement (Grace, 1977). This growth alteration is primarily hormonal in nature and characterized by increased radial enlargement and reduced stem elongation resulting in a shorter, bushier plant (Jaffe, 1976a; Mitchell et al., 1975).

Crop yields in terms of plant dry matter are affected by mechanical wind stress (Hunt and Jaffe, 1980; Russell and Grace, 1979a). Not only is plant yield affected, but plant cellular composition or quality is affected as well (Armbrust et al., 1974; Greig et al., 1974). Increased crop yields in shelter may be due to a reduction in mechanical wind stress as well as microclimate modification (Sturrock, 1975). If mechanical stress is reduced in shelter, anatomical changes may occur and affect crop quality as well. Whether there is a significant increase or decrease in sheltered crop quality harvested for its dry matter yield, the literature is vague and needs further clarification.

Forms of mechanical stress such as wind, bending, shaking, and rubbing are known to produce the same effect on plant growth and development (Jaffe, 1980). Developmental responses to shaking, rubbing, and bending stimuli have been termed 'thigmomorphogenesis'(Jaffe, 1973) whereas responses to shaking or vibrational stimuli have been called 'seismomorphogenesis' (Mitchell et al., 1975). Both of these terms characterize the effects of mechanical wind stress on plant form and structure and are used interchangeably in the literature. To establish consistency of terms, thigmomorphogenesis will be used to describe the effects of various mechanical stimuli on plant growth in this thesis.

Kinetics of Thigmomorphogenesis

The sequence of events underlying the response to mechanical stimulation in several species occurs as follows: after mechanical stimulation, there is an immediate increase in the growth rate that lasts 2 to 3 minutes (Jaffe, 1973). Following this, growth stops completely for 15 to 45 minutes. Then the growth rate resumes at about one half the pre-stimulus rate. If the plant is not stimulated again it will regain its original growth rate within 2 or 3 days, depending upon the species (Jaffe, 1973; 1976a). Thus, the thigmomorphogenetic response is a rapid one, with the first measurable reaction occuring instantaneously (Jaffe, 1980). This phenomenom seems to be a form of physiological stress rather than physical damage (Larson, 1965; Mitchell et al., 1975). Since no injury is involved, the plant is free to resume the normal rate of growth after several days (Jaffe, 1980).

Integrative Mechanisms in Thigmomorphogenesis

Mechanical stimulation is linked to growth retardation in plants by a chain of casual relationships (Jaffe, 1980). Mechanically stressed plants show no injury symptoms except altered growth, suggesting a change in hormonal patterns (Salisbury and Ross, 1978). How a change in hormone balance might come about is still unclear. Jaffe (1976b) has shown that during the early events of thigmomorphogenesis, electrical resistance (cell membrane permeability to solutes) of bean stems decrease greatly within a few seconds after rubbing, followed by a slower rise back toward the normal level. Changes in cell membrane permeability such as this can rapidly affect the availability of hormones at the subcellular sites where they are effective. Also these changes may affect subsequent production of hormones which would alter growth (Salisbury and Ross, 1978).

Role of Hormones

There is a reason to believe that mechanical stimulation of plant tissue induces the production of the gaseous plant hormone, ethylene (Jaffe, 1980). Mechanical stimulation of herbaceous plants induces epinasty in the leaves and causes internodes to increase markedly in diameter and elongate less (Jaffe, 1973; Mitchell et al., 1975; Saltveit and Larson, 1983). These morphological modifications appear to be related to increased ethylene production. Inhibitors of ethylene significantly nullify growth retardation due to mechanical stimulation and ethylene is the only phytohormone that, when applied exogenously, precisely mimics all the morphological effects of mechanical stimulation (Jaffe and Biro, 1979). Biro and Jaffe (1984) showed that the pulse of ethylene produced by mechanical stress directly mediates the thickening response. However, it is not yet clear if endogenous ethylene mediates the decrease in elongation directly or indirectly. Apparently, factors other than ethylene may be involved in the changes occuring in stressed bean plants (Huberman and Jaffe, 1981).

The growth hormone, auxin, also seems to be involved in thigmomorphogenesis. Victor and Vanderhoef (1975) and Mitchell (1977) have demonstrated that mechanical stress reverses auxin promoted elongation in soybeans and peas (*Pisum sativum* L.). Jaffe (1980) has shown that auxin-like substances accumulate in internodes that have been mechanically stressed or treated with exogenous ethylene and that a high concentration of exogenous auxin causes growth retardation in bean internodes. Thus, ethylene production seems to block basipetal auxin transport since mechanical stress has been reported to do this in peas (Mitchell, 1977). This causes auxin to accumulate in the internode to such an extent that it induces further ethylene production (Jaffe, 1980).

Callose Formation

A lack of information exists concerning the sequence of events following mechanical stimulation, between the first observed rapid changes in electrical resistance of plant tissue and the subsequent initiation of ethylene evolution (Biro and Jaffe, 1984). It is proposed that an elicitor may be the connecting factor between the two events. Elicitors are part of the plant's defense mechanism for resistance to various stresses (Salisbury and Ross, 1978). Takahashi and Jaffe (1984) indicated that mechanical stress produces elicitor-like activity which can induce ethylene production. Jaffe et al. (1985) have suggested that callose could be acting as the elicitor inducing ethylene production. Callose is formed in the plant for development of phloem sieve plates (Salisbury and Ross, 1978) and for use in plant wound healing processes (Dekayos, 1972).

Plants subjected to mechanical stress showed an immediate response of callose deposition in the sieve tubes and companion cells of the vascular system. The callose accumulated very quickly, peaking after about 6 hours and then gradually disappearing 3 days later (Jaffe et al., 1985). The disappearance of callose coincided with the reappearance of the pre-stimulus elongation rate after 3 days, when plants have been mechanically stressed only once (Jaffe, 1973; 1976a). In plants receiving mechanical stress daily, growth continued to be retarded and callose deposition continued. These correlations coupled with the fact that an inhibitor (2-deoxy-D-glucose) could block both stem thickening and callose deposition, suggest that callose deposition is an early part of the causal chain leading to thigmomorphogenesis (Jaffe et al., 1985).

Effect on Plant Processes

There have been few studies performed concerning the effects of mechanical stress on plant physiological processes. Wadsworth (1960) has shown that at very low windspeeds, plants benefit due to increased assimilation rates. From his work there appears to be an optimum windspeed of about 0.3 m/s (Wadsworth, 1959). However, at higher windspeeds, plant processes are adversely affected (Todd et al., 1972).

The effect of thigmomorphogenesis on plant processes is thought to be due to the mechanical damage of plant tissue and individual cells. Studies have shown that cells of shaken leaves fail to function normally. Experimental vibration of leaves resulted in increased respiration, diminished photosynthesis and transpiration, usually closure of stomata and marked reduction of plant growth, even with very short periods of treatment (Sturrock, 1975).

Todd et al., (1972) has shown that wind increases plant respiration by mechanical stimulation. They examined the respiration of *Magnolia grandiflora* L. leaves, both restrained and unrestrained from movement by wires. The results indicated that unrestrained leaves respired 13% more than restrained leaves and 40% more than unexposed leaves. Audus (1935) and Godwin (1935) also showed that gentle rubbing or bending of leaves caused a two-fold increase in the rate of respiration. Reductions in net photosynthesis may also result from increased respiration due to shaking (Kahl, 1951).

A study by Mitchell et al. (1977) concerning photosynthesis showed that a mechanical stress induced decline in dry weight was attributed to reduced photosynthetic surface. This was suggested by the parallel effects of stress on leaf area and whole plant dry weight over time. Mitchell and his colleagues hypothesized that reduced photosynthetic productivity from thigmomorphogenesis is the result rather than the cause, of a general growth reduction, perhaps hormonal in nature. However, a more recent study by Pappas and Mitchell (1983) found lower transpiration rates and higher water potentials in leaves of thigmo-stressed plants indicating that mechanical stimulation may also reduce plant growth by affecting stomatal aperature and thus CO_2 assimilation.

Effect on Plant Morphology

The most common thigmomorphogenetic response, which is found in a wide variety of plant species, is retardation of stem elongation accompanied by an increase in stem thickness (Jaffe, 1973). In greenhouse experiments, Turgeon and Webb (1971) discovered that daily shaking of squash (Cucurbita melopepo L.) for 30 seconds resulted in a decrease in length and fresh weight of stems and petioles. The petioles also indicated an increase in radial growth. Similar reductions in stem length and shoot fresh weight were noted in sunflower (Helianthus annuus L.) including a smaller leaf surface area (Beyl and Mitchell, 1983).

Neel and Harris (1972) showed that daily shaking of corn for 30 seconds over a period of 25 days resulted in reductions of 50% in height, 30% in visible leaf number, and 15% in leaf length. However, when the stressed plants were no longer shaken each day, the height-growth rate was equal to that of the unstressed plants after 3 days. Such marked responses from short periods of movement suggested that a growth influencing mechanism of a hormonal nature is involved.

Akimoto et al., (1979) investigated the effects of wind on rooting and growth of tobacco at constant environmental conditions. They found that the stem length, leaf area, and dry leaf weight were less than the controls. Dry root weight of the wind-treated plants was less than the controls even though roots of the wind treated plants grew longer and reached deeper into the soil. Because of poor top growth caused by the wind, a smaller root/shoot ratio resulted.

Hunt and Jaffe (1980) tried to establish the phenomenom of thigmomorphogenesis in herbaceous plants in a wind exposed field. They used kidney bean (Phaseolus vulgaris L.) plants and confirmed the results of greenhouse experiments. Statistical analysis of the data indicated significant differences in stem elongation and diameter between sheltered and exposed kidney bean plants. Furthermore, there was a strong relationship between the amount of wind and the amount of thigmomorphogenesis. They determined that this relationship may in fact be logarithmic, although a linear function fits well in the range of wind velocities studied.

A very good example of the general effects of thigmomorphogenesis is the work done by Mitchell et al., (1975). They studied the effects of mechanically stimulating tomato plants in the greenhouse by shaking, flexing, and rubbing the plant stems. They found that stressed plants were sturdier, shorter, and bushier than controls. Foliage of stressed plants tended to be "leathery" in appearance, deep green in color, and epinastic, symptoms generally associated with growth retardant application. Stem growth inhibition was measured over a 35 day period as a once daily (1x) and twice daily (2x) 30 second gyrotory shaking. During the treatment period, stem growth of the stressed plants lagged increasingly behind the controls, resulting in reductions of 42.1 and 59.1% for the (1x) and (2x) shaking treatments respectively. Growth patterns of fresh and dry weight were similar to those for stem length. Although stressed plants appeared to be more lignified than controls, there were no significant changes in succulence (fresh/dry wt.).

Another sign of growth reduction in tomato was a lag in the initiation of new nodes and leaves with increasing time of stress. It may be expected that developmental processes dependant upon a certain minimum node number (i.e., flowering) may be significantly delayed by brief daily stress treatments (Mitchell et al., 1975).

Nodal swelling is another manifestation of mechanical stress response to plants. The normal thickening of the tomato cotyledonary node for example, was accelerated by shaking. All other nodes of the stressed plants also thickened with increased plant height, more than the control plants. Petiolar thickening in the stressed plants was also noted. Although controls possessed more lateral branches, stressed plants developed 2 to 3 times the lateral growth of the controls (Mitchell et al., 1975).

The effect of manual stem flexing on chlorphyll content (as an index of greening) in tomato was determined after 10.5 days of stress. While the absolute content of chlorophyll was unchanged between stressed and unstressed plants, the lower shoot fresh weight of the stressed plants resulted in a one-third increase in relative chlorophyll content/unit fresh weight. Their interpretation of the apparent greening was that the smaller cell size and slower growth rate of stressed plants, represented a concentration of the normal chloroplast compliment within a smaller cellular volume (Mitchell et al., 1975).

Effect on Plant Anatomy

The studies mentioned thus far have sought to demonstrate that mechanical stress such as results from wind action can be expected to play an important role in shaping the character and size of most plants in the natural environment. Attention needs to be given to the anatomical changes occuring in the mechanically stressed plant. In the future this may be important for crop quality determinations. If environmental mechanical stress tends to produce a plant more capable of withstanding stress, then the strengthening elements in the plant tissues are changed or enhanced (Grace and Russell, 1977). Grace and Russell (1977) have shown that wind-blown leaves of tall fescue have a greater modulus of elasticity than controls. Similarly, thigmo-stressed bean stems were greatly strengthened against mechanical breakage by previous mechanical stimulation. Their strengthening was attributed to an increase in stem flexibility, but not in their stiffness (Jaffe et al., 1984).

Biro et al., (1980) defined the anatomical changes in bean stems due to mechanical stimulation. The decrease in stem elongation was due to reduced elongation of cells in the outer tissues, such as the epidermis, and in the axial cell divisions of the inner tissues, especially the pith and secondary xylem. Mechanically stressed sunflower produced more xylem and thicker cell walls than did controls (Whitehead, 1962). Stem pithiness due to drought stress was reduced in tomato when they were pretreated with mechanical stimulation (Pressman et al., 1983).

Venning (1948) showed that celery (Apium graveolens L.) exposed to wind motion developed more collenchyma, a fiberous tissue that is supposed to confer mechanical strength. Similarly, Heuchert et al. (1983) observed that stems of shaken tomato plants developed a "fiberous" appearance, whereas those of controls remained "succulent". In response to shaking young tomato seedlings, they found no change in stem fiber content. Fiber components, including hemicellulose, lignin, and silica plus ash, did not change significantly, but the cellulose component increased by 15%. Possible responses of these stem fiber components to shaking older plants remain to be determined. Since cellulose is largely responsible for the elastic strength of plant cell walls, the greater modulus of elasticity of stems of shaken plants corresponds well with their enhanced cellulose content.

ALFALFA GROWTH AND DEVELOPMENT

Alfalfa is a herbaceous perennial legume that is grown throughout North America as a source of high quality forage for livestock (Smith, 1970). It has a high mineral content and contains at least 10 different vitamins including vitamin A in large amounts. Alfalfa is a very desireable ration component for ruminant livestock because of its high digestibility and crude protein content, the major proportion of which is found in the leaves (Barnes and Sheaffer, 1985).

Alfalfa has pinnately trifolialate leaves arranged alternately on the stem. A mature alfalfa plant may have from 5 to 25 stems that arise from a woody crown and usually reaches a height of 60-90 cm. The root system has a distinct taproot, which under favorable conditions may penetrate the soil 7 to 9 m or more. Alfalfa is well adapted to a wide range of climatic and soil conditions. It grows best in deep loam soils with porous subsoils and good drainage (Barnes and Sheaffer, 1985).

Alfalfa grows well on irrigated fertile soils in the drier climate of western Nebraska (Lawson, 1977a; 1977b). Irrigation of alfalfa is less effective on many soils in the eastern part of Nebraska because there is usually sufficient rainfall (Lawson, 1977a). Added water can also cause increased losses due to poor soil aeration and root and foliar diseases (Barnes and Sheaffer, 1985).

In eastern Nebraska, 3 or 4 alfalfa cuttings per growing season are normally harvested, usually at the 1/10 bloom stage to obtain high yields of good quality forage. Second or successive alfalfa cuttings normally result in yields less than the first cutting (Hoy, 1976). Alfalfa quality measured in terms of crude protein and IVDMD will drop to lower levels with increased physiological maturity. It also changes from cutting to cutting throughout the growing season (Baumgardt and Smith, 1962; Reid et al., 1959). Unfortunately, when alfalfa quality is at its highest, the yield is low (Elliott et al., 1972).

Alfalfa stand dynamics affect the yield and quality of alfalfa forage. Increased yields are obtained when plants/m^2 and stems/m^2 are high, producing fewer but heavier tillers per plant (Mullen et al., 1977). Decreases in plant population produce more tillers per plant that are lighter in weight. Fewer plants with lighter stems causes yield reductions (Cowett and Sprague, 1962; Mullen et al., 1977).

Changes in plant population also alter stem structure and composition. An increase in the number of stems per plant is often accompanied by increased leaf:stem ratios, resulting in improved forage digestibility and crude protein content (Cowett and Sprague, 1962). Whole plant digestibility of alfalfa forage is primarily dependent on the leaf:stem ratio and the amount of lignin and fiber in the cell walls of the stem (Barnes and Gordon, 1972; Luckett et al., 1967). Leaves are highly digestible and remain at a nearly constant level of digestibility during maturation whereas stems are lower in digestibility and decline steadily in digestibility during maturation (Luckett and Klopfenstein, 1970). Leaves contain more crude protein than stems and primarily determine the crude protein content of the plant at a specified maturity (Meyer et al., 1960).

Height of the alfalfa stand is very closely correlated with lignin and protein content irrespective of year, cutting, or stage of maturity. As plant height increases, protein content drops because of lower leaf:stem ratios (Meyer et al., 1960). Structural components such as cellulose, hemicellulose, and lignin increase as plants get tall resulting in lower digestibility (Mascola et al., 1971). Tall forage is also associated with high alfalfa yields because of the increased amounts of stem material (Elliott et al., 1972).

Yield and quality of alfalfa is largely controlled by the prevailing environment. The two major environmental factors that influence alfalfa growth are air temperature and soil moisture. Optimum air temperatures for alfalfa growth are between 15 and 25^{o}C during the day and between 10 and 20^{o}C at night (Vough and Marten, 1971). Temperature studies under controlled environmental conditions confirm conclusions from field studies that the primary effects of warmer temperatures on alfalfa growth and development are hastened maturity and a concomitant decline in quality

(Garza et al., 1965; Jensen et al., 1967). Alfalfa harvested at specific growth stages under warm vs cool temperature regimes was higher in crude protein (Smith, 1969; Vough and Marten, 1971), leaf percentage (Faix, 1974; Marten, 1970), and lignin (Vough and Marten, 1971). However, warm temperatures decreased IVDMD, height, and dry matter yield (Smith, 1969; Vough and Marten, 1971).

Optimum soil moisture under field conditions may increase the crude protein content of alfalfa (Bezeau and Sonmor, 1964; Groskopp et al., 1963) or have no effect (Carlton et al., 1968; Kilmer et al., 1960; Vough and Marten, 1971). Too much soil moisture can reduce yields and lower the quality. Irrigation at a 50% level of minimum available soil moisture produced higher dry matter yields of alfalfa, and a higher percentage of crude protein and *in vitro* digestible cellulose, than either higher or lower levels of irrigation (Bezeau and Sonmer , 1964). With increased soil moisture, *in vitro* digestibility of leaf and stem fractions was lower, and the proportion of highly digestible fractions (leaf and flower) were also decreased (Snaydon, 1972). Reduced yield brought about by low soil moisture resulted in a stunted, leafier plant, which was lower in fiber and lignin and more digestible (Jensen et al., 1967).

MATERIALS AND METHODS

STUDY AREA

The study was initiated in the spring of 1983 with the establishment of a perennial alfalfa crop at the University of Nebraska, Agricultural Research and Development Center, Mead, Nebraska (41° 10' N latitude, 96° 25' W longitude). Alfalfa growth parameters were measured under exposed and sheltered field conditions during the following growing seasons of 1984 and 1985.

The site consisted of a 20 ha field protected from the wind by a tic-tac-toe system of shelterbelts established in 1966 for windbreak research. In 1982 the tic-tac-toe system was altered by removing tree rows extending from the center square southward and westward leaving four of the original nine tic-tac-toe squares intact (Figure 1). Each remaining square was commonly protected from the southerly winds by shelterbelts on the south and west sides. These squares provided four replicated protection zones from the wind. The shelterbelts were two rows in width and consisted of Scotch pine (*Pinus sylvestris* L.), and eastern redcedar (*Juniperus virginiana* L.), averaging 6 m high and about 70% dense. Exposed areas produced by tree line removal from the tic-tac-toe design were used as treatment comparisons to sheltered zones.

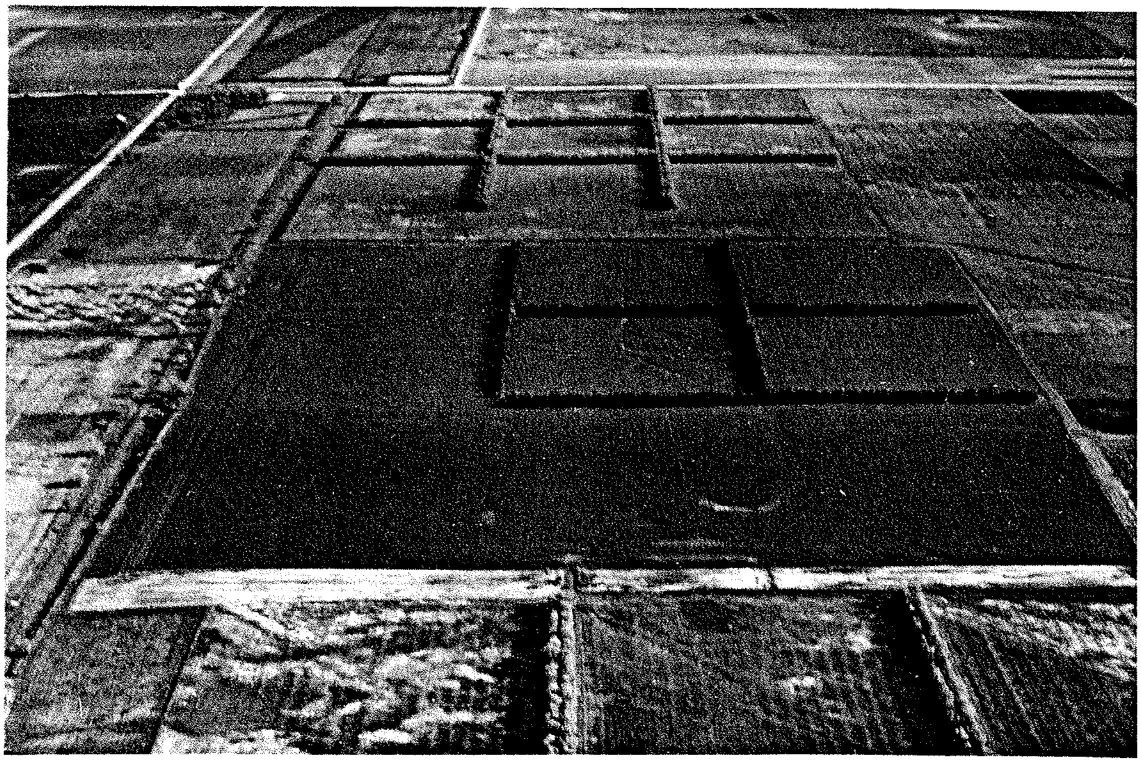

Figure 1. Aerial photograph of modified tic-tac-toe shelter-belt system (bottom). Normal tic-tac-toe arrangement is at top. Top of photograph is north.

The field is composed of soils in the Sharpsburg-Fillmore association (Typic Argiudoll), which is characterized by deep, dark, moderately clayey and clayey, nearly level soils. Sharpsburg, 0-2% slope, is the dominant soil type with small areas of Fillmore, 0-2% slope, silty clay loam soil in the lower, poorly drained areas of the field. The Sharpsburg soil has a deep, moderately well drained top soil with moderately slow permeability. Natural fertility is high and the organic matter content is moderate. Available water storage capacity is 25.5 cm down to a depth of 150 cm (Elder et al., 1965). Volumetric soil moisture content averages 36% at field capacity and 19% at the wilting point with an average bulk density of 1.33 g/cm^3 (Garay, 1981).

Climatic conditions at the experimental site include a sub-humid environment with an average rainfall of 690 mm; 74% of which falls during the growing season (April through September) (Elder et al., 1965). Maximum growing season temperatures range from 23.3° to 39.4°C and the minimum growing season temperatures range from 3.9° to 19.4°C (Nollette, 1983). Frequent changes occur in wind direction at all seasons of the year, but the prevailing direction from May to September is from the south or southeast, and from the northeast or north during the remainder of the year. During June, July, and August, hot dry southwest winds often cause serious and extensive damage to crops (Elder et al., 1965). Average annual windspeed is 4.7 m/s (NOAA, 1978).

TREATMENT DESIGN AND APPLICATION

The experiment was designed to measure the effect of wind condition (shelter vs exposed) and soil moisture regime (dryland vs irrigated) on dry matter yield, plant height, leaf:stem ratio, plant density, stem density, stems per plant, crude protein (leaves, stems, and whole plant), *in vitro* dry matter digestibility (leaves, stems, and whole plant) and available soil moisture content. The experiment utilized a split split-plot design with wind condition as the whole plot treatment, soil moisture regime as the subplot treatment, and cuttings as the split split-plot treatment conducted without re-randomization during the growing season. Whole plots were approximately 16,384 m^2 (128 X 128 m) in size and layed out in the form of a completely randomized design with four replications per wind condition treatment. Physical limitations in relocating wind condition treatments among whole plots prevented actual randomization.

Whole plots were planted to 'Perry' alfalfa on May 1, 1983. Establishment of the alfalfa stand consisted of applying benifin herbicide preplant at a rate of 1.15 l/ha, followed by double disking and firming the soil with a corrugated roller. Alfalfa seed inoculated with rhizobia (*Rhizobium meliloti*) bacteria was drilled into 18 cm rows at a rate of 14 kg/ha. Phosphorous fertilizer was incorporated into the soil prior to seeding to bring soil nutrients up to recommended levels as determined by soil tests. During the year preceding seedling establishment, the field was fallowed and the soil limed to adjust soil pH levels to pH 6.5.

Seedling emergence ocurred in 7 days. However, after 21 days of growth, the stand was diminished due to a fungal investation of damping off (Helminthosporium spp.) disease. All areas of the field were infected but enough plants survived to provide a satisfactory alfalfa stand. Plant density taken at the end of the 1983 growing season indicated 80 $\pm$ 22 plants/m^2 in the exposed and 86 $\pm$ 17 plants/m^2 in the sheltered areas. Three cuttings of alfalfa were harvested during the year of establishment.

Subplots were approximately 274 m^2 (6 X 45.7 m) in size and randomly located in designated areas to satisfy sheltered and exposed whole plot treatment specifications. Subplot shelter effects were measured at a distance of 7H (H = average tree height) leeward of the south and west tree rows. Measurements were only obtainable at one leeward location because of the size and design of the experiment. 7H was chosen because it is the approximate midpoint of the wind protection zone (1H to 15H) that occurs behind a field shelterbelt. Measurements in this location would give a good indication of the overall shelter effect on crop growth parameters in the protection zone. Exposed subplots were located 97.2 m windward of the shelterbelt system and thus outside their area of influence (Rosenberg, 1974). Subplot variables were measured by obtaining subsamples from three randomly located 4 m^2 (1 X 4m) plots permanently fixed within the field (Figure 2).

Alfalfa cuttings represented successive measurements on whole and subplot treatments over the growing season. Harvest periods were pre-determined using early maturity stages to facilitate obtaining four cuttings within a growing season. Cuttings were scheduled to be harvested at maturity stages of late bud, 1/10 bloom, 1/10 bloom, and late bud respectively. Subplot and subsample plots were not re-randomized for every cutting. Physical limitations prevented movement of the irrigation system for subplot re-randomization.

Water was supplied for irrigation treatments by using a tow line irrigation system modified to apply water according to the line-source sprinkler method (Hanks et al., 1976). Sprinkler application was designed to be uniform out to 2 m perpendicular to a single lateral pipeline and along its length. Subsample plots were located within 2 m of the pipeline and parallel to it (Figure 2). Rain guages were placed next to each plot to determine application amounts.

Irrigations were scheduled based on soil moisture deficits down to 150 cm. Remaining usable moisture divided by the predicted daily water use rate determined the number

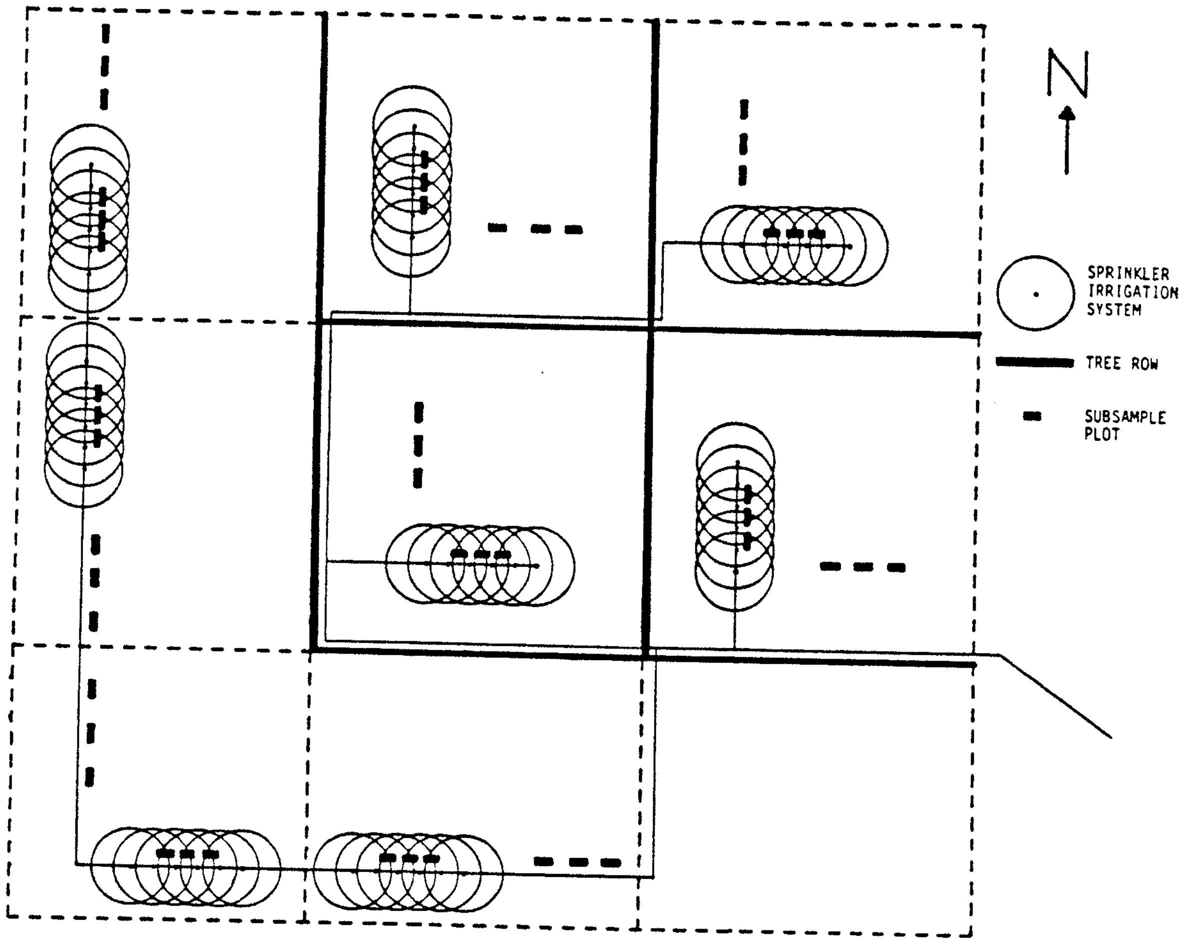

Figure 2. Experimental layout.

of days before the next irrigation (Eisenhaur et al., 1979). Adequate moisture and aeration for best plant growth are in the 50 to 85% available soil moisture range (Peterson, 1972). Available soil moisture down to 150 cm was maintained between 13 and 22.1 cm of water, a difference of 9.1 cm water. Irrigation water was applied to fill the soil profile up to 85% of field capacity. Irrigations were sometimes postponed or cancelled when a possibility of rain existed or the windspeed was too great.

SOIL MOISTURE MEASUREMENT

Available volumetric soil moisture content was estimated in each treatment area weekly with a neutron probe device (Troxler Model 3220 Moisture Depth Guage). Aluminum access tubes were placed at one end of each subsample plot to a depth of 150 cm. Measurement counts were taken in the midpoint of the 0-30; 30-60; 60-90; 90-120; and 120-150 cm soil layers.

The neutron probe was calibrated for this experimental site. Gravimetric soil moisture samples were obtained at the time of tube installation and followed by neutron probe readings at 30 cm intervals to create a calibration curve for the neutron-scattering method (Figure A.1). A linear equation was used to convert count ratio (actual neutron count/standard neutron count) to percent volumetric moisture content (Pv). The calibration equation is as follows:

$$Pv = 55.477(\text{count ratio}) - 9.67$$

Neutron probe readings at each depth were converted to volumetric water content, then to centimeters of water, and finally to centimeters available water by subtracting wilting point water content from each water content determination. The total available water in the 150 cm soil profile was obtained by adding the available water for all depth increments.

METEOROLOGICAL MEASUREMENTS

Microclimatic conditions surrounding the plant were characterized by measuring windspeed, air temperature, and precipitation. Cup-anemometers were used to measure windspeed at a height of two meters in both wind condition treatments. Measurements to calculate percent wind reduction were taken at a distance of 7H leeward from the shelterbelt. Maximum and minimum air temperatures were recorded immediately above each irrigated and dryland crop canopy. Wind direction and rainfall data were collected 200 m southeast from the study area by an automated weather station operated by the University of Nebraska, Center for Agricultural Meteorology and Climatology. During the winter, snow accumulation within the sheltered and exposed treatment areas were visually noted for differences in depth.

PLANT MEASUREMENTS

Plant growth parameters were measured prior to each cutting throughout each growing season. Measurements were taken from the subsample plot or from a designated quadrant of the subsample plot. Plant maturity, leaf:stem ratio, plant density, stem density, stems per plant, and quality analysis were determined from plants clipped from within a 0.25 m^2 (0.5 X 0.5 m) frame placed in a designated corner of the subsample plot. Plant maturity was estimated by counting the number of buds or the number of stems in bloom. Plant height measurements were taken in four random subsample plot locations using a meter stick. Plant density was determined by the number of plants rooted within the frame. Plants within the frame were clipped at 5 cm, sealed in plastic bags and returned to the field laboratory to be weighed for fresh weight. The subsample plot was then cut with a sickle bar mower and the cut forage weighed on a hanging scale to determine fresh weight.

In the laboratory, alfalfa stems were counted and the forage placed in a forced air oven (50^{o}C) until dry. Oven dried forage yield was calculated by multiplying percent dry matter by the fresh weight of the subsample. After drying, leaves were separated from stems by hand to determine the leaf:stem ratio. Leaves and stems were ground separately in a Wiley Mill through a 1 mm screen and sealed in twist lock plastic bags for forage quality analysis.

Forage quality analysis consisted of analyzing samples for crude protein content and *in vitro* dry matter digestibility (IVDMD). Crude protein was measured using the Macro-Kjeldahl method (AOAC, 1975) and IVDMD was determined by the Tilley and Terry (1963) two-stage technique modified to include 1 g urea per liter of buffer used. McDougall buffer (McDougall, 1948) and rumen liquor were combined in a 50:50 ratio. Rumen inoculum was obtained from two rumen-fistulated steers on separate diets of alfalfa hay and ground corn cobs, 16 hours postfeeding. Fermentation of 0.5 g samples lasted 48 hours and was followed by acid-pepsin digestion for 24 hours.

STATISTICAL ANALYSIS

Analysis of variance procedures were performed on plant, soil moisture, and meteorological data using the general linear model of SAS (SAS Institute Inc., 1982) (Table 1). Main treatment effects and interactions were tested for significance at the 0.10 level. When statistically significant effects were detected, Fisher's (protected) LSD (0.10) was used for mean separation. Standard errors for a difference between wind condition means within or among soil moisture regimes were calculated by:

$$S.E. = \sqrt{2[(m-1)E_b+E_a]/rm}$$

Table 1. Form of the analysis of variance for a split split-plot experiment in alfalfa with a completely randomized design in the whole plot. The experiment utilized successive measures (cuttings) without re-randomization during the growing season.

Single-year Analysis

Source of Variation	DF		Expected Mean Squares
Wind Condition[W]	w-1		$\sigma^2 + cm\sigma^2_{R(W)} + rcm\theta_W$
Replication(Wind)	w(r-1)	E_a	$\sigma^2 + cm\sigma^2_{R(W)}$
Moisture Regime[M]	m-1		$\sigma^2 + c\sigma^2_{MR(W)} + rcw\theta_M$
Mois*Wind	(m-1)(w-1)		$\sigma^2 + c\sigma^2_{MR(W)} + rc\theta_{MW}$
Mois*Rep(Wind)	w(m-1)(r-1)	E_b	$\sigma^2 + c\sigma^2_{MR(W)}$
Cutting[C]	c-1		$\sigma^2 + m\sigma^2_{CR(W)} + rwm\theta_C$
Cut*Wind	(c-1)(w-1)		$\sigma^2 + m\sigma^2_{CR(W)} + rm\theta_{CW}$
Cut*Rep(Wind)	w(c-1)(r-1)	E_c	$\sigma^2 + m\sigma^2_{CR(W)}$
Cut*Mois	(c-1)(m-1)		$\sigma^2 + rw\theta_{CM}$
Cut*Mois*Wind	(c-1)(m-1)(w-1)		$\sigma^2 + r\theta_{CMW}$
Cut*Mois*Rep(Wind)	w(c-1)(m-1)(r-1)	E_d	σ^2

W Whole plot effect (shelter vs exposed)
M Subplot effect (dryland vs irrigated)
C Split split-plot effect (cutting)

r Number of replications
w Number of wind condition treatments
m Number of soil moisture regime treatments
c Number of cuttings

E_a Whole Plot error
E_b Subplot error
E_c Split split-plot error
E_d Split split-plot error

Standard errors for a difference between wind condition means within soil moisture regimes, within cuttings were calculated by:

$$S.E. = \sqrt{2[E_a+mE_b+cE_c+(cm-m-c-1)E_d/rcm]}$$

Data for each year was analyzed separately. The alfalfa experiment utilized successive measures (cuttings) without re-randomization during the growing season; hence the analysis involved a split-plot in space and time approach to successive measures (Steel and Torrie, 1980).

Successive measures for soil moisture were performed by date instead of cutting. For windspeed analysis, successive measures were taken over main effects only, and tested for significance at the 0.05 level.

RESULTS AND DISCUSSION

CHARACTERIZATION OF THE ENVIRONMENT

Climatological Data

The growing seasons of 1984 and 1985 presented variable growing conditions with regard to precipitation (Figure A.2) and average daily temperature (Figure A.3). Weather patterns during the 1984 growing season (April through September) consisted of a cool wet period during the months of April, May, and June followed by mild to moderate drought conditions for the remainder of the growing season (NOAA,1984). Temperatures in April and May averaged 2^{o}C below normal while the rest of the season had near normal temperature conditions (Table A.2).

The 1985 growing season was a good year for alfalfa production. There was adequate precipitation for good alfalfa growth and it was well distributed throughout the growing season. Average temperatures were warmer than normal during April and May of 1985 but were slightly cooler than the normal during the remainder of the growing season (NOAA, 1985).

Snowfall during both years of data collection had a negligible influence on treatment effects. Low snowfall amounts resulted in accumulations of only 15 to 20 cm on both exposed and sheltered plots. Snow accumulation in the sheltered plots was primarily due to dead alfalfa vegetation catching the blowing snow rather than wind reduction by the shelterbelt.

Windrun

Wind reduction for each cutting during the 1984 and 1985 growing season is illustrated in Figure 3. Percent wind reduction at a distance of 7H was similar for each cutting for both years with mean wind reductions of 41.0 and 40.3% for sheltered plots during 1984 and 1985 respectively. Windrun was significantly reduced ($P<0.05$) in sheltered alfalfa plots during the 1984 and 1985 growing season (Table A.3).

Windrun reductions of approximately 40% would be expected to have a beneficial effect on the microclimate surrounding the crop to improve its growth and yield. Excluding the effect of increased moisture from snow accumulation, windrun reductions of 40% or somewhat less have been shown to significantly increase the growth and yield of cotton (Barker et al., 1985), soybeans (Radke and Burrows, 1970), snap beans (Rosenberg et al., 1967), and millet (Ujah and Adeoye, 1984). However, the beneficial effect of windrun reduction on crop growth and yield is diminished if turbulence increases substantially in the lee of the shelterbelt (Siddoway, 1970). Turbulent wind causes bending and shaking of plant parts which inhibit physiological processes and morphological development (Jaffe, 1980).

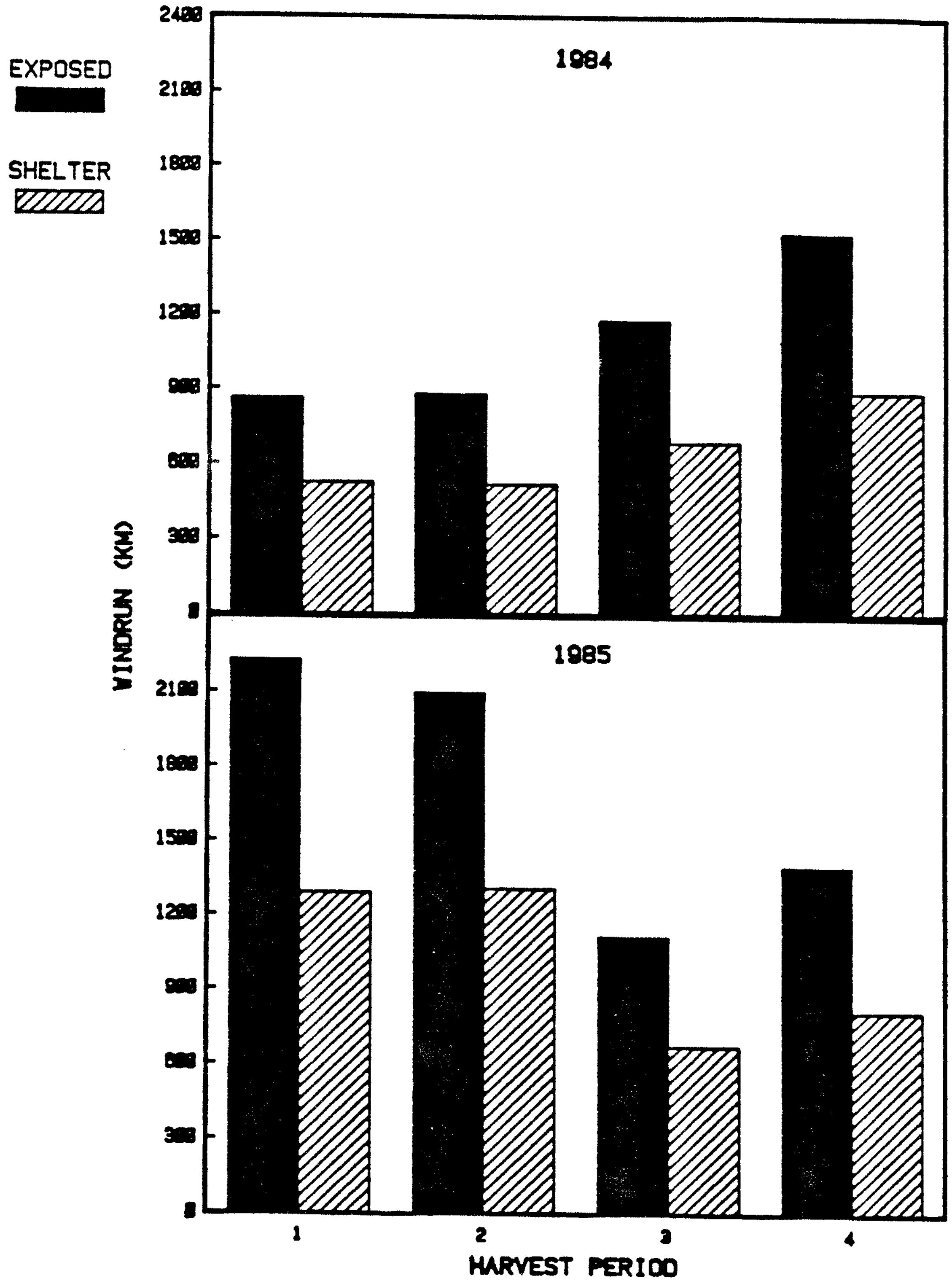

Figure 3. Windrun amounts in exposed and sheltered plots for each cutting during the 1984 and 1985 growing season.

It also increases vertical diffusion and mixing of the air, minimizing the shelter effect on microclimate (Miller et al., 1974; McNaughten, 1987). Shelterbelts reduce leeward turbulence velocity fluctuations below windward values close to the belt, but turbulent fluctuations increase in the leeward direction to eventually exceed windward values (Heisler and DeWalle, 1987). Dense belts such as the ones used in this thesis study, produce the largest turbulent fluctuations at all leeward positions (Hagen and Skidmore, 1971). Therefore, the beneficial effect of windrun reduction on microclimate and crop parameters at a distance of 7H may of been negated to some degree. This is reinforced by the lack of statistically significant differences between exposed and sheltered treatments for most of the parameters measured.

Air Temperature

Seasonal trends of maximum and minimum air temperatures measured in sheltered and exposed plots under dryland and irrigated moisture regimes for each cutting during 1984 and 1985 are shown in Figures A.4 through A.7. No significant differences ($P<0.10$) were detected for maximum or minimum air temperatures between exposed and sheltered plots under dryland and irrigated conditions (Tables A.4 and A.5).

The lack of air temperature differences between exposed and sheltered alfalfa plots at a leeward distance of 7H may be the result of increased turbulence caused by high barrier density. Typically in many sheltered situations, higher daytime and lower nighttime air temperatures are observed due to reduced vertical diffusion and mixing of the air (Skidmore, 1969). Temperature increases during the day within 10H of the barrier are generally confined to $2^{\circ}C$ and night air temperature usually differ only slightly (Hagen and Skidmore, 1971; Marshall, 1967; Ujah and Adeoye, 1984). Behind dense shelterbelts, these conditions commonly occur close to the belt where windspeed is reduced the most and turbulent air overtopping the belt has not yet reached the crop surface. This turbulent air reaches the crop surface at closer leeward distances than behind more porous belts, causing increased vertical diffusion and mixing of the air.

Hagen and Skidmore (1971) have shown that lateral and vertical wind velocity fluctuations increase markedly at a distance of 6H to the lee of high density barriers. In this area, the mean vertical air flow was downward, bringing the cooler air from above into the air layer above the crop canopy. Woodruff et al. (1959) and Skidmore et al. (1972) have observed the same turbulent air flow behind dense barriers resulting in little or no changes in air temperatures. At further leeward distances (10 to 12H), the air temperatures actually became cooler then in the open field. The lack of statistically significant air temperature differences at a distance of 7H in this study may have been caused by the same turbulent air flow patterns reported by the for-mentioned authors.

Soil Moisture

Available soil moisture measured to a depth of 150 cm in dryland and irrigated plots subjected to sheltered and exposed wind conditions during the 1984 and 1985 growing season is shown in Figures 4 through 7. A continuous soil moisture curve could not be determined for 1984 because of malfunctioning of the neutron soil moisture probe. More weekly readings were obtained during 1985 providing a near continuous curve of available soil moisture content.

For both years, soil moisture content in sheltered and exposed alfalfa plots was at or near field capacity (100% available soil moisture) at the beginning of the growing season. In both years as the growing seasons progressed, soil moisture gradually declined. In early to mid-July, available soil moisture approached 50% depletion initilizing soil moisture recharge by irrigation in the irrigated treatment plots. These plots were maintained between 50 and 85% of field capacity by irrigation for the remainder of both seasons.

Dryland plots dropped to moisture levels of 50% or lower later in the growing season (Figures 4 and 6). During 1984, dryland plots reached their lowest soil moisture levels with measurements of 33% (8.5 cm) and 23% (5.9 cm) in

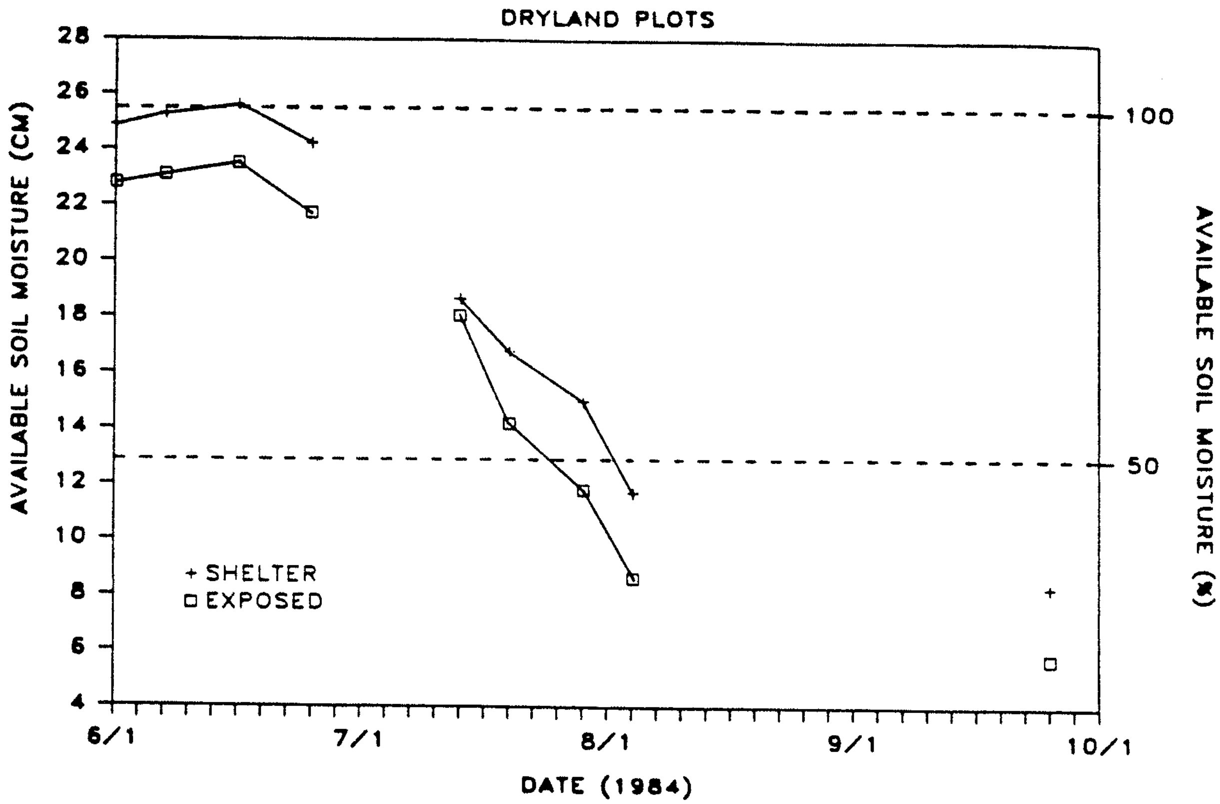

Figure 4. Available soil moisture in sheltered and exposed dryland plots measured to a depth of 150 cm during the 1984 growing season.

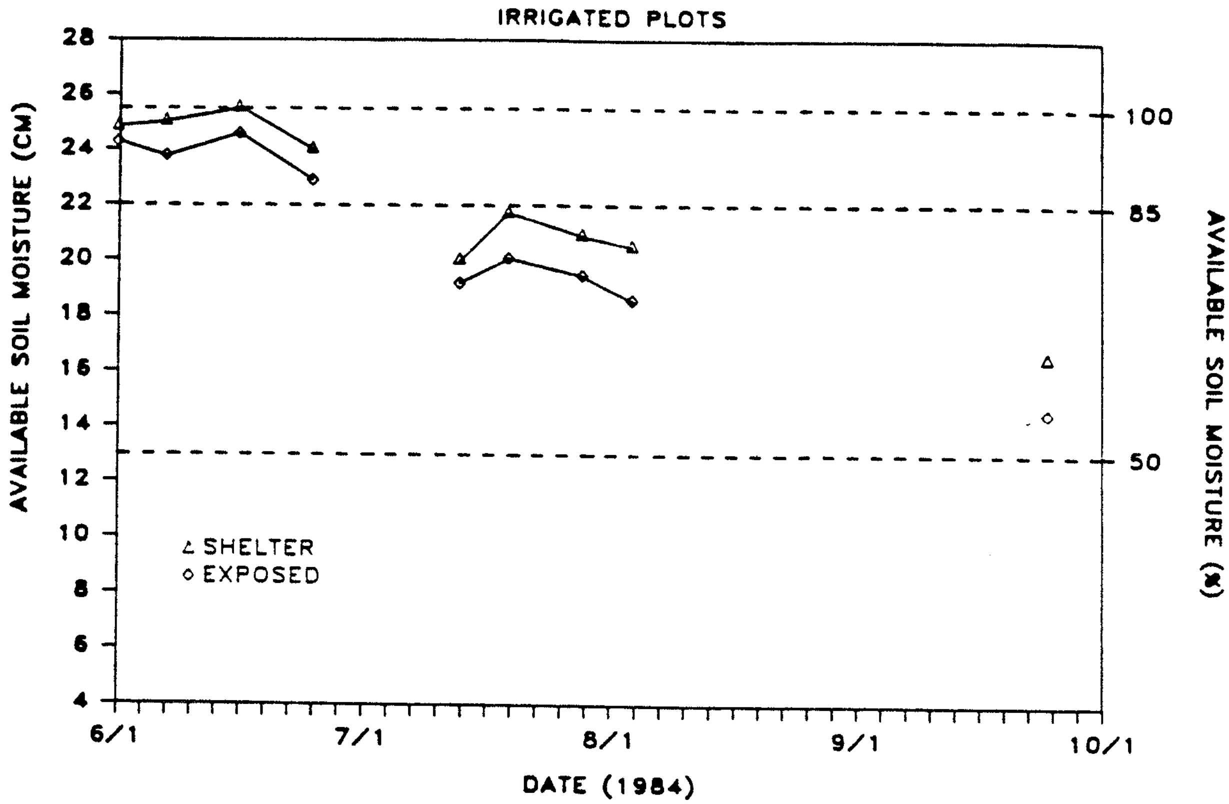

Figure 5. Available soil moisture in sheltered and exposed irrigated plots measured to a depth of 150 cm during the 1984 growing season.

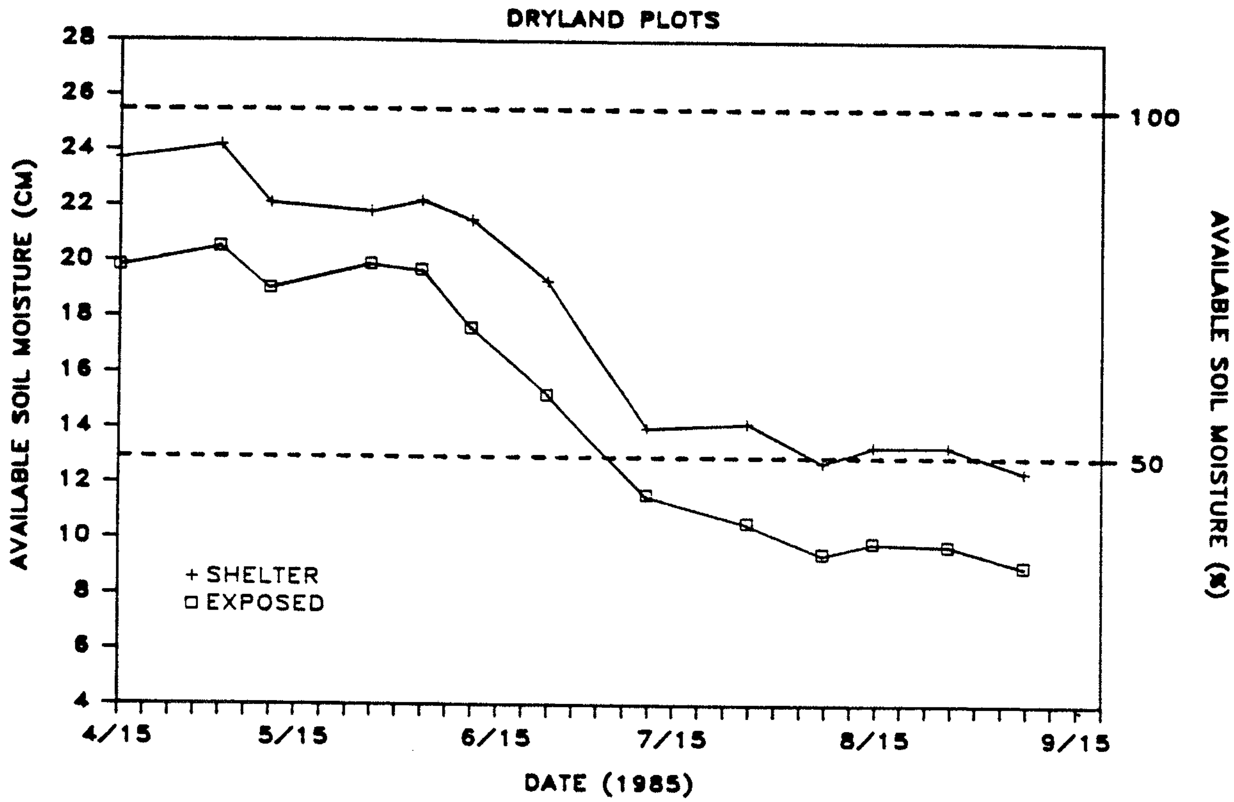

Figure 6. Available soil moisture in sheltered and exposed dryland plots measured to a depth of 150 cm during the 1985 growing season.

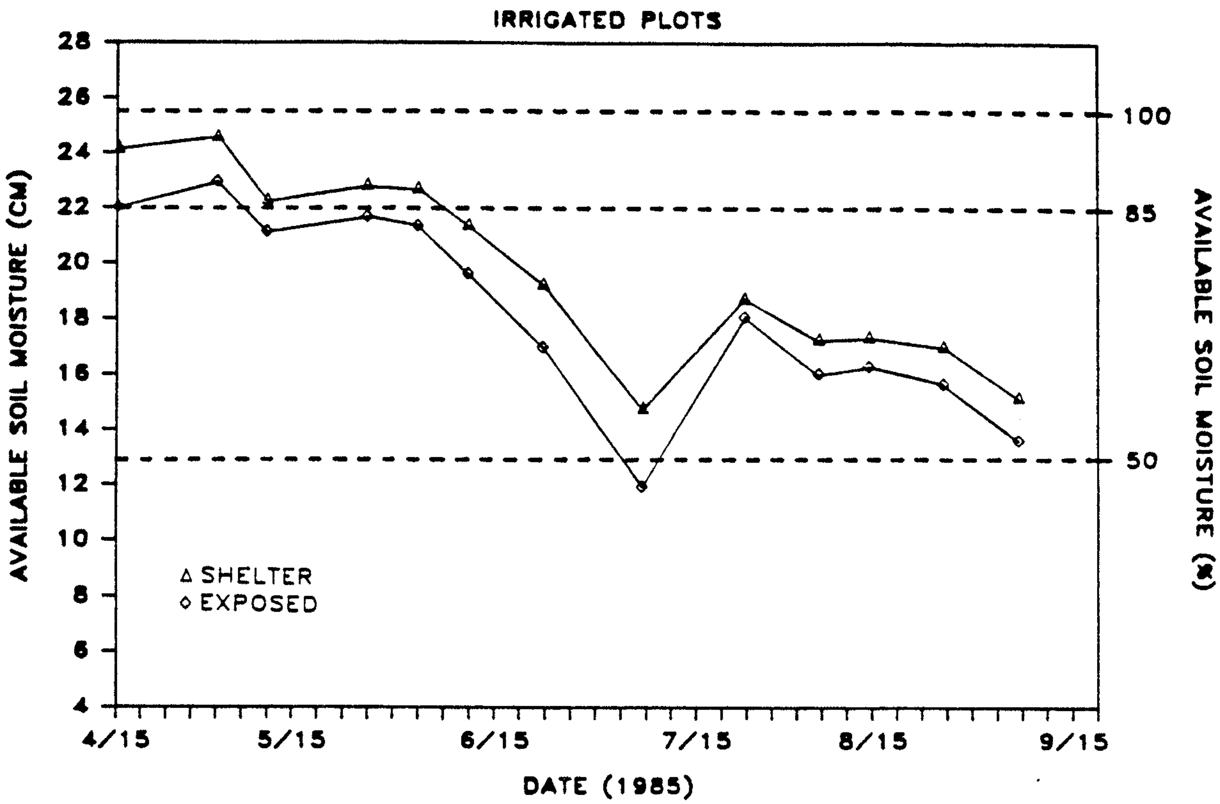

Figure 7. Available soil moisture in sheltered and exposed irrigated plots measured to a depth of 150 cm during the 1985 growing season.

sheltered and exposed plots (Table A.6). At these levels, alfalfa may have experienced some moisture stress. Little difference in alfalfa yield will occur at available soil moistures in the range of 35-85% but yield reductions can occur if levels drop below 25-30% (Kansas State University, 1978). Rainfall was distributed more evenly throughout the 1985 growing season and provided higher dryland soil moisture levels near 50% in the later part of the summer (Figures 6 and A.2).

Available soil moisture measurements were consistently greater in sheltered plots for all sampling dates throughout both growing seasons. Sheltered dryland and irrigated plots averaged 2.3 and 1.0 cm more soil moisture than exposed plots during 1984, and 3.3 and 1.6 cm more during 1985 for all dates measured. However, for both years, sheltered values were not significantly different ($P<0.10$) from exposed values for either dryland or irrigated treatments (Tables A.6 and A.7).

Other authors have reported no significant differences in soil water use between sheltered and exposed crops, such as irrigated snap beans (Rosenberg et al., 1967), dryland soybeans (Radke and Burrows, 1970; Ogbuehi and Brandle, 1981), and dryland millet (Ujah and Adeoye, 1984). These authors have attributed the lack of soil moisture differences to greater vegetative growth and increased yields in the sheltered areas. These plants required more water for growth and thus prevented the beneficial effect of shelter on soil moisture to be measured. In this study alfalfa growth parameters and alfalfa yield were not significantly different between exposed and sheltered plots within irrigated and dryland moisture regimes suggesting that the lack of soil moisture differences were not due to greater vegetative growth in the sheltered plots.

The lack of significant differences in available soil moisture between sheltered and exposed alfalfa plots may be attributed to the influence of dense shelterbelts on evapotranspiration at further distances from the belt such as 7H. Windspeed reduction by a shelterbelt reduces evapotranspiration which in turn influences soil moisture levels (Miller et al., 1974). Excessive turbulence caused by dense shelterbelts, transport water vapor rapidly away from the sheltered zone promoting further evaporation (van Eimern, 1966). The increased loss of water vapor due to turbulence may have offset the moisture savings from windspeed reduction in this sheltered situation (Siddoway, 1970). As a result there were no differences in available soil moisture between exposed and sheltered plots.

Irrigation

Greater soil moisture trends in shelter, although not statistically significant, resulted in reduced application amounts of irrigation water in shelter. Irrigated shelter plots required 2.3 cm less irrigation water than exposed plots during 1984 and 2.2 cm less during 1985 (Table A.8). Irrigated plots received 5 applications during 1984 because of the dry weather later in the growing season (Figure A.2). During 1985 only one application was given due to the better distribution of rainfall throughout the summer. Although the irrigation water savings were small, it appears that shelterbelts may be a means for increasing water use efficiency in irrigated agriculture by reducing the amount of irrigation water needed, maybe more so during drier years.

SHELTER EFFECT ON GROWTH PARAMETERS

Height

The influence of shelter on alfalfa height is illustrated in Figure 8. During both years of data collection, shelter had no significant effect ($P<0.10$) on plant height under either dryland or irrigated moisture conditions. Significant differences between sheltered and exposed treatments were also not apparent for any one cutting during either of the growing seasons. Trends in the data collected during 1984 indicated increases in mean plant height of 2.5 and 0.8% in dryland and irrigated sheltered treatments respectively. During 1985, shelter increased mean plant height in both dryland and irrigated treatments 5.1

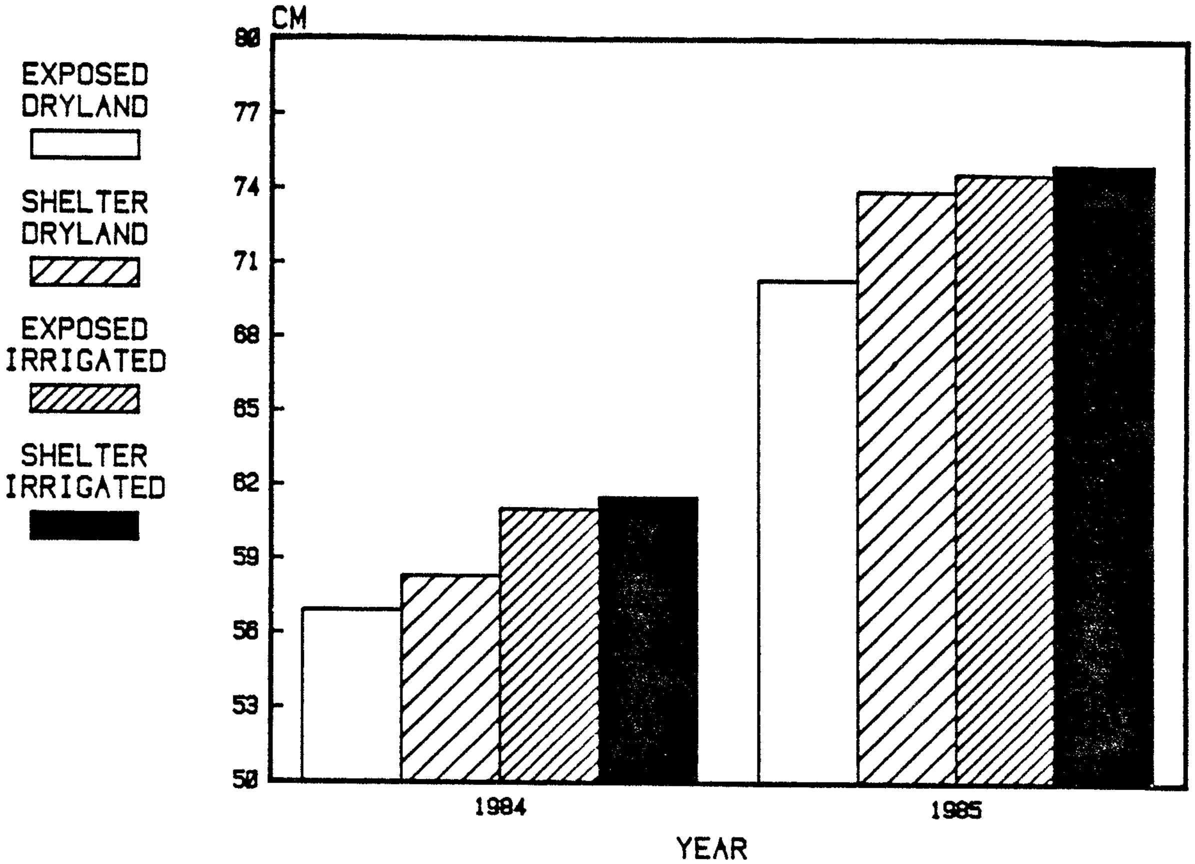

Figure 8. Seasonal mean plant heights of dryland and irrigated alfalfa subjected to exposed and sheltered wind conditions during the 1984 and 1985 growing season.

and 0.5% respectively (Table A.9). Taller plants during 1985 were mainly the consequence of better rainfall distribution throughout the growing season.

High alfalfa yields are often associated with tall forage (Elliott et al., 1972). Windbreak induced increases in plant height have been reported for crops such as soybeans (Radke and Burrows, 1970), wheat (Skidmore et al., 1974), oats (Sturrock, 1981), and cotton (Barker et al., 1985). This increase in plant height has been shown to cause greater spatial separation of leaves within the canopy of sheltered plants resulting in better penetration of incident photosynthetically active radiation (Ogbuehi and Brandle, 1981). As a result, sheltered plants performed better in terms of dry matter production. In this study the failure of shelter to significantly affect alfalfa height under dryland or irrigated conditions suggests that alfalfa yields were not benefited due to taller plants.

Leaf:Stem Ratio

Shelter effects on alfalfa leaf:stem ratio is presented in Figure 9. During both years of data collection, shelter had no significant effect ($P<0.10$) on leaf:stem ratio under either dryland or irrigated moisture conditions (Table A.10). Significant differences between sheltered and exposed treatments were also not apparent for any one cutting during either of the growing seasons. Trends in the data collected

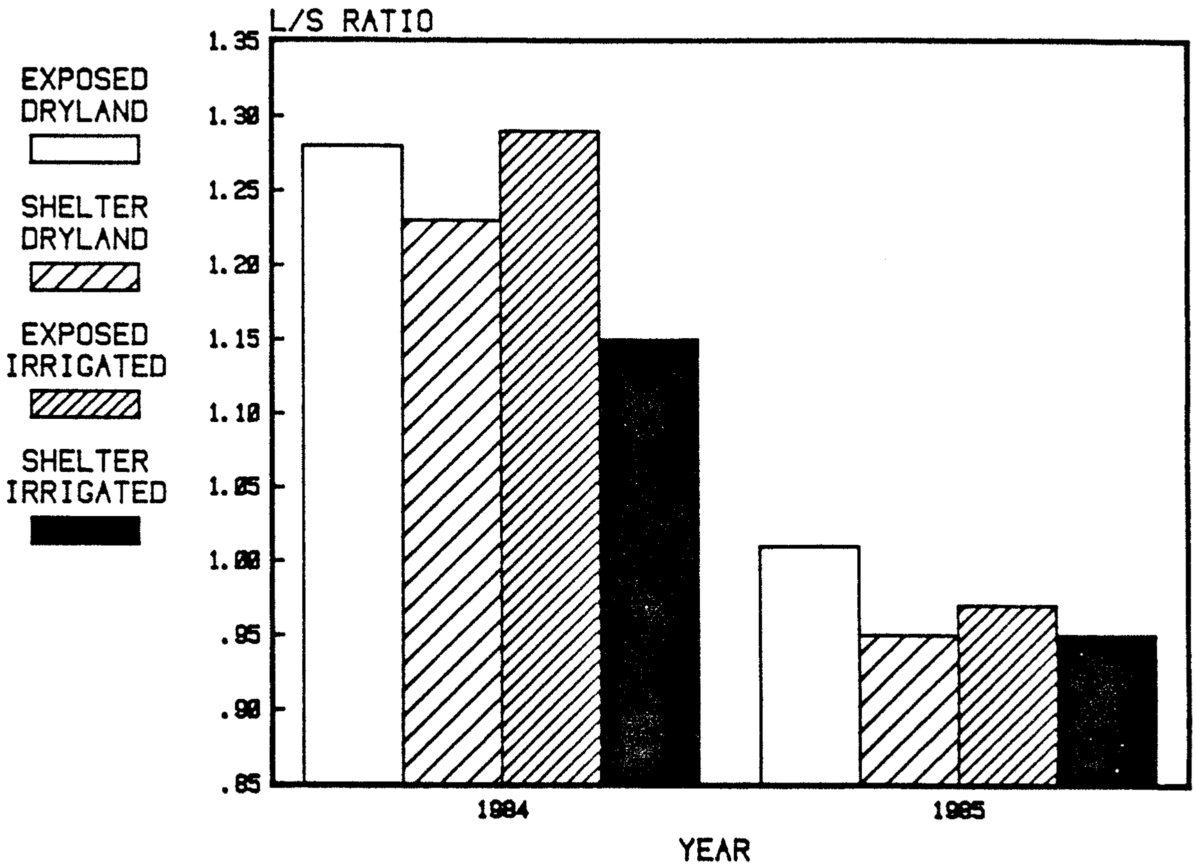

Figure 9. Seasonal mean leaf:stem ratios of dryland and irrigated alfalfa subjected to exposed and sheltered wind conditions during the 1984 and 1985 growing season.

during 1984 showed shelter to decrease mean leaf:stem ratios 3.9 and 10.9% in dryland and irrigated sheltered treatments respectively. During 1985, shelter decreased mean leaf:stem ratios 5.9 and 2.1% in dryland and irrigated sheltered treatments respectively. Lower mean leaf:stem ratios during 1985 as compared to 1984 can be associated with taller plants having more stem tissue relative to leaf tissue (Figures 8 and 9).

Alfalfa forage quality is very dependent on the leaf:stem ratio. Higher whole plant crude protein and digestibility levels are obtained when the proportion of leaves versus stems is increased (Terry and Tilley, 1964; Vough and Martin, 1971). Shelter has been shown to increase the amount of leaf material in crops such as snap beans (Rosenberg et al., 1967), sugar beets (Brown and Rosenberg, 1971), perennial grasses (Russell and Grace, 1979b), soybeans (Ogbuehi and Brandle, 1981), and cotton (Barker et al., 1985). However, in this study shelter failed to significantly affect the amount of alfalfa leaf material, and thus did not improve the quality of the forage.

Plant Density, Stem Density, and Stem Number Per Plant

The effect of shelter on plant density, stem density, and stem number per plant is illustrated in Figures 10, 11, and 12 respectively. During both years of data collection, shelter had no significant effect ($P<0.10$) on these seasonal

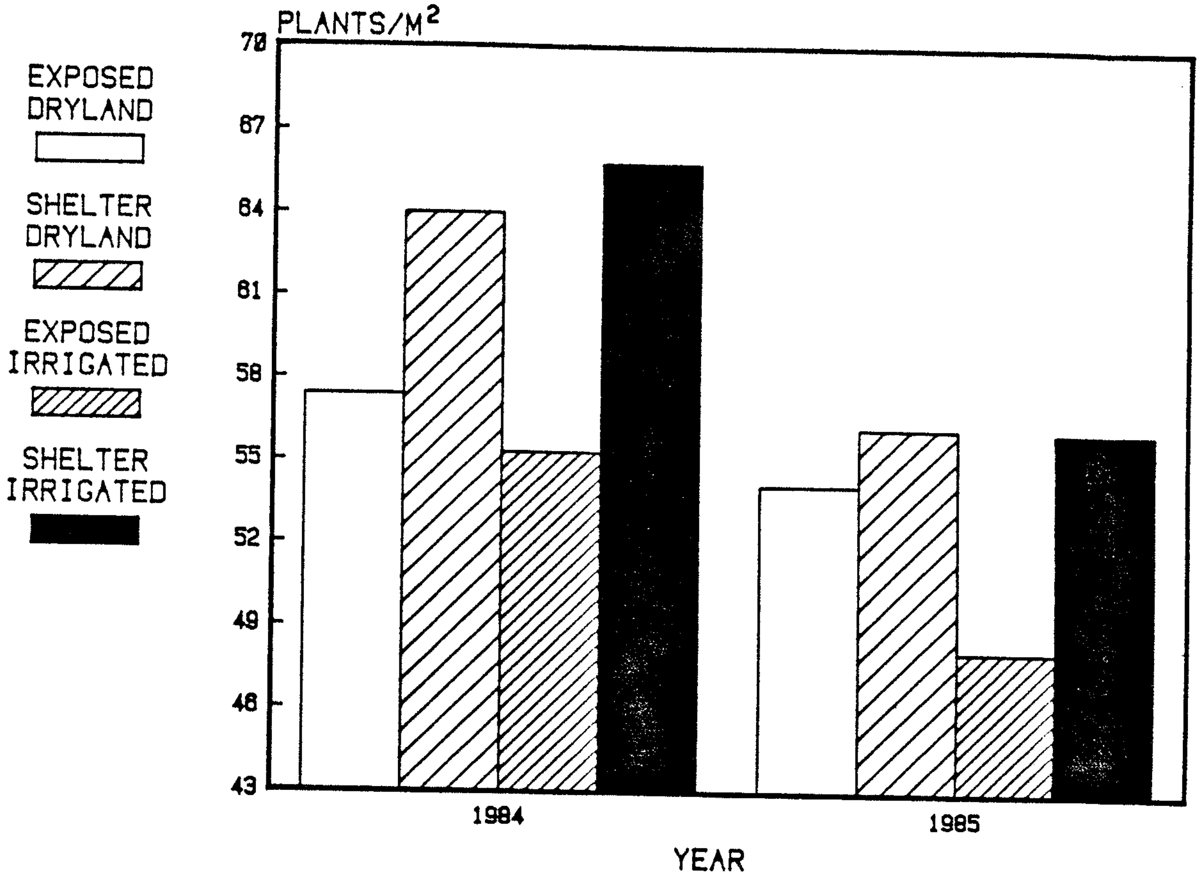

Figure 10. Seasonal mean plant densities of dryland and irrigated alfalfa subjected to exposed and sheltered wind conditions during the 1984 and 1985 growing season.

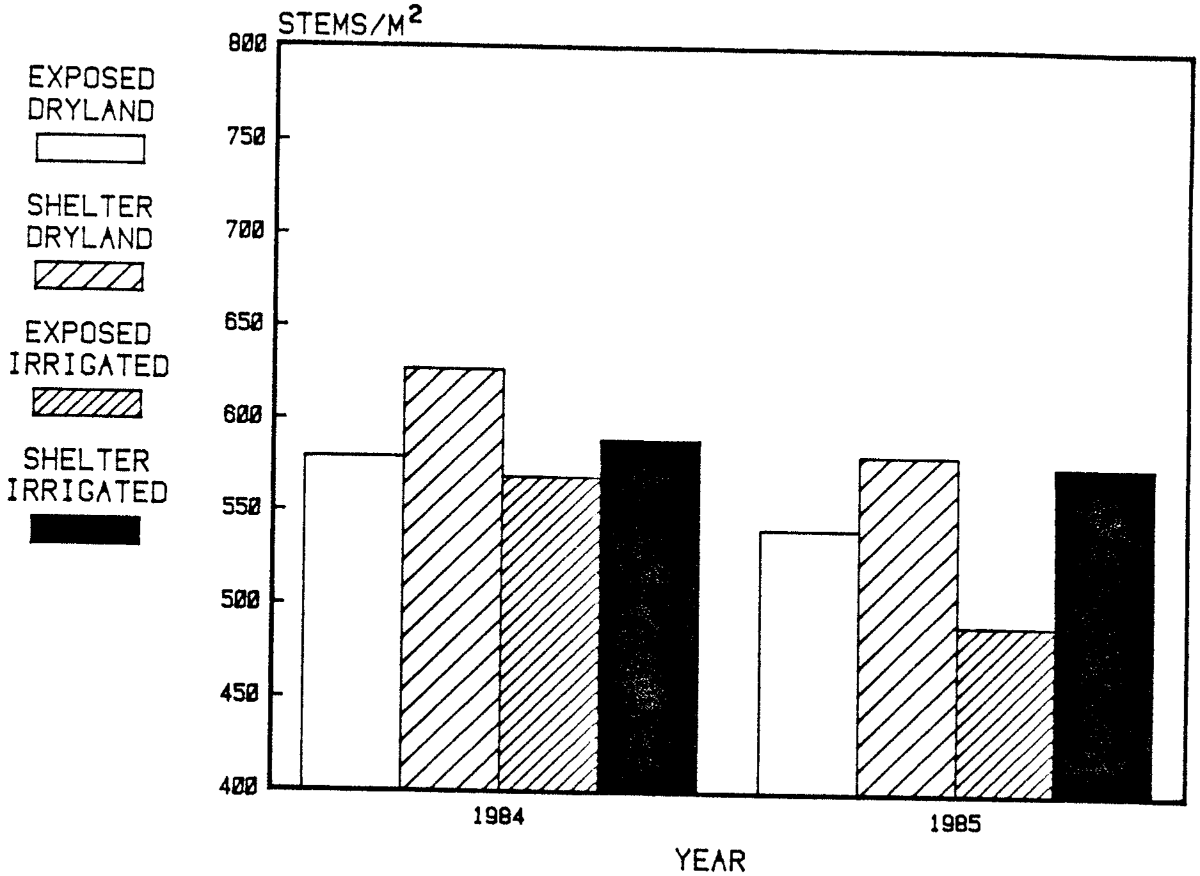

Figure 11. Seasonal mean stem densities of dryland and irrigated alfalfa subjected to exposed and sheltered wind conditions during the 1984 and 1985 growing season.

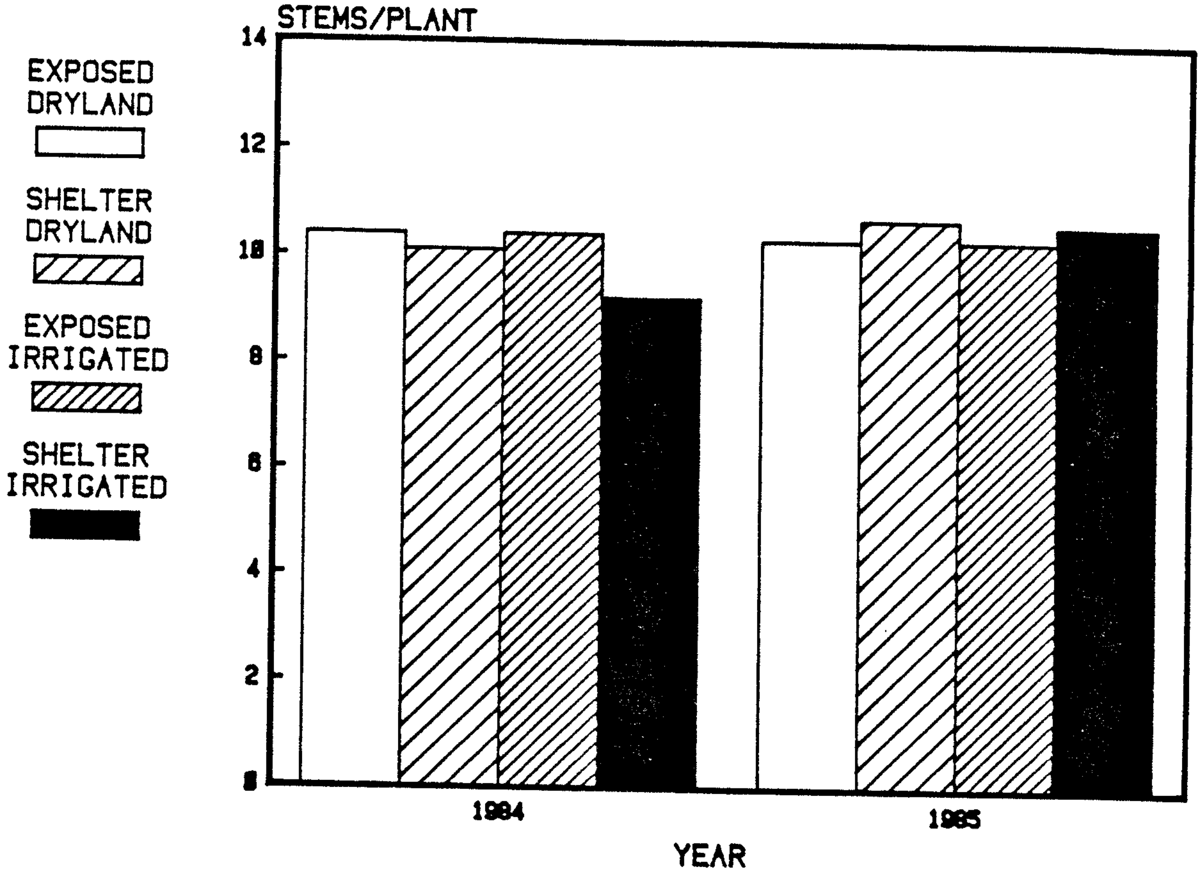

Figure 12. Seasonal mean stem number per plant of dryland and irrigated alfalfa subjected to exposed and sheltered wind conditions during the 1984 and 1985 growing season.

mean growth parameters under either dryland or irrigated moisture conditions (Tables A.11, A.12, and A.13). Significant difference between sheltered and exposed treatments were also not apparent for any one cutting during either of the growing seasons. Trends in the data showed shelter to affect 1984 dryland and irrigated seasonal treatment means by increasing plant density 11.5 and 19.0%, increasing stem density 8.2 and 3.6%, and decreasing stems per plant 2.9 and 11.5% respectively. During 1985, shelter affected dryland and irrigated seasonal treatment means by increasing plant density 3.9 and 16.6%, increasing stem density 7.4 and 17.5%, and increasing stems per plant 3.9 and 2.9% respectively. Lower plant and stem densities during 1985 were probably the result of plant mortality caused by increasing age of the alfalfa stand (Figures 10 and 11). This change in alfalfa stand composition was not great enough, however, to effect stem number per plant (Figure 12).

Increases in alfalfa yield can be obtained when plant density and stem density are high, producing fewer but larger and heavier stems per plant (Mullen et al., 1977). In this study, measurements of plant density, stem density, and stem number per plant were not significantly affected by shelter. Thus alfalfa yield was not affected by shelter through changes in these growth parameters.

SHELTER EFFECT ON ALFALFA YIELD

Dry matter yields of sheltered and exposed alfalfa plots subjected to dryland and irrigated moisture regimes are illustrated in Figure 13. During both years of data collection, shelter had no significant effect ($P<0.10$) on seasonal mean alfalfa yields under either dryland or irrigated conditions. Significant differences between sheltered and exposed treatments were also not apparent for any one cutting during either of the growing seasons (Table A.14). These results showed that at a leeward shelterbelt distance of 7H and a wind reduction of approximately 40%, shelter had no significant effect on alfalfa yield.

Changes in alfalfa yield due to shelter were small. Trends in the data collected during 1984 showed increases in sheltered dryland and irrigated seasonal mean alfalfa yields of 9.1 and 0.5% respectively. During 1985 seasonal mean alfalfa yields were decreased 0.6% in the dryland sheltered treatment and increased 0.5% in the irrigated sheltered treatment (Table A.14). Seasonal mean alfalfa yields were similar for both growing seasons except for the exposed dryland treatment. This treatment yielded better in 1985 probably as a result of better rainfall distribution during that growing season (Figures 13 and A.2).

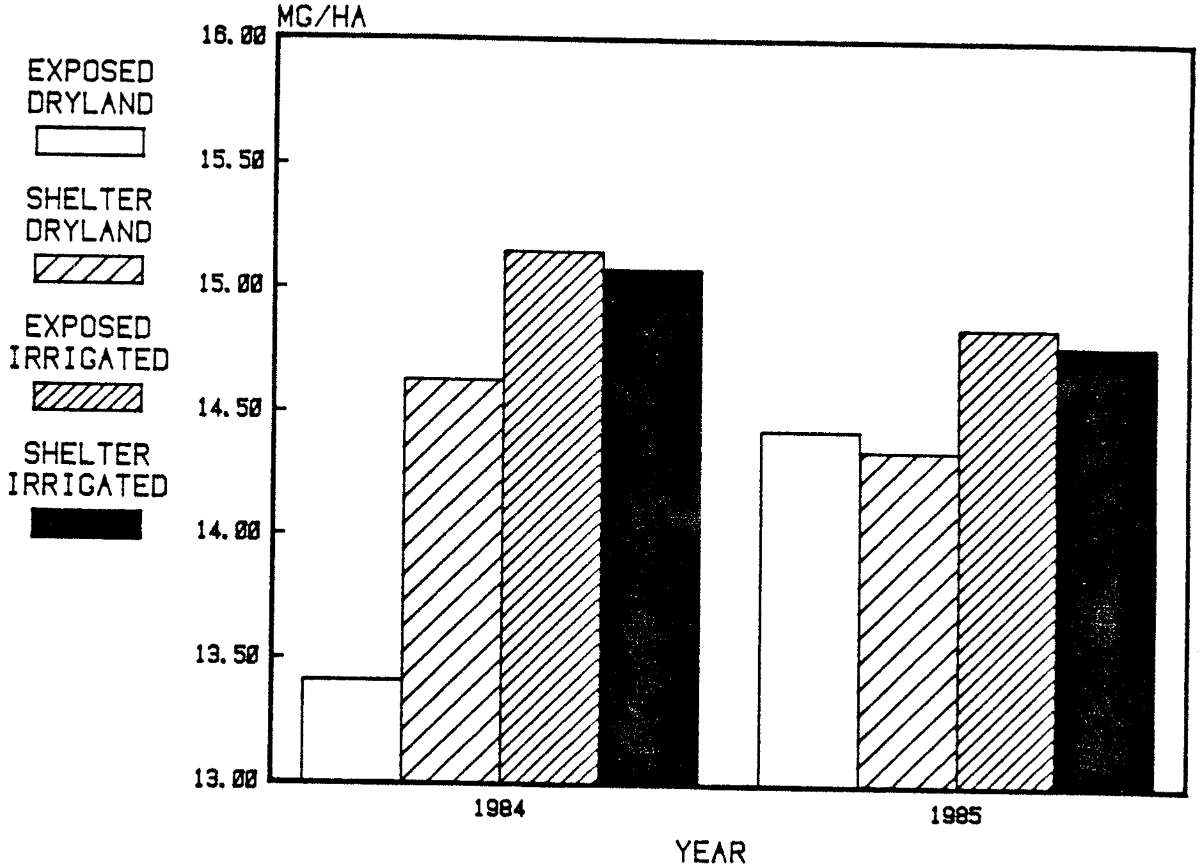

Figure 13. Seasonal mean dry matter yields of dryland and irrigated alfalfa subjected to exposed and sheltered wind conditions during the 1984 and 1985 growing season.

These small and nonsignificant yield differences were unexpected and are in contrast to most of the previously published literature. Past shelterbelt research performed in a number of countries has shown yield increases ranging from 22 to 203% in dryland alfalfa (Jensen, 1954; van Eimern, 1964) and yield increases of 21% in irrigated alfalfa due to shelter (Farnworth, 1974). However, most of these yield increases were obtained at closer leeward distances to the shelterbelt than 7H where there is more wind reduction especially behind dense belts.

Similarities between sheltered and exposed alfalfa yields were supported by growth parameter measurements. Shelter had no significant effect on alfalfa growth parameters associated with yield potential such as plant height, plant density, stem density, and stem number per plant. The beneficial effect of shelter on these growth parameters was not great enough to ultimately result in significantly improved dry matter yields.

SHELTER EFFECT ON ALFALFA QUALITY

The effect of shelter on alfalfa quality in terms of crude protein and *in vitro* dry matter digestibility (IVDMD) are presented in Tables 2 through 7. During both years of data collection, shelter had no significant effect ($P<0.10$) on seasonal mean alfalfa crude protein content or IVDMD of

Table 2. Leaf crude protein per cutting of dryland and irrigated alfalfa subjected to exposed and sheltered wind conditions during the 1984 and 1985 growing season.

Year/ Cutting	Exposed		Sheltered		
	Dryland	Irrigated	Dryland	Irrigated	$LSD_{0.10}$
1984			%		
1	26.7	27.0	27.0	26.9	NS
2	28.3	28.2	25.0	27.4	NS
3	26.5	26.3	25.9	26.6	NS
4	26.7	27.4	27.2	27.7	NS
Mean	27.1	27.2	26.3	27.1	NS
1985					
1	24.8	25.1	24.5	24.8	NS
2	26.0	25.4	26.3	26.2	NS
3	27.7	27.5	27.5	28.1	NS
4	28.5	28.1	27.8	28.0	NS
Mean	26.8	26.5	26.5	26.8	NS

Table 3. Stem crude protein per cutting of dryland and irrigated alfalfa subjected to exposed and sheltered wind conditions during the 1984 and 1985 growing season.

Year/ Cutting	Exposed		Sheltered		
	Dryland	Irrigated	Dryland	Irrigated	$LSD_{0.10}$
1984		%			
1	11.2	12.0	12.5	12.1	NS
2	10.6	10.6	10.2	10.5	NS
3	10.2	9.9	9.9	10.0	NS
4	10.9	11.0	11.3	11.2	NS
Mean	10.7	10.9	11.0	11.0	NS
1985					
1	10.5	10.6	10.3	10.4	NS
2	9.8	9.8	9.7	9.7	NS
3	10.7	11.0	10.9	10.9	NS
4	11.3	11.2	11.1	11.4	NS
Mean	10.6	10.7	10.5	10.6	NS

Table 4. Whole plant crude protein per cutting of dryland and irrigated alfalfa subjected to exposed and sheltered wind conditions during the 1984 and 1985 growing season.

Year/ Cutting	Exposed		Sheltered		
	Dryland	Irrigated	Dryland	Irrigated	$LSD_{0.10}$
		%			
1984					
1	19.1	19.5	19.6	19.4	NS
2	20.9	21.2	19.0	20.3	NS
3	19.6	18.4	18.6	18.5	NS
4	19.9	20.0	20.2	20.0	NS
Mean	19.9	19.8	19.4	19.6	NS
1985					
1	16.8	17.2	16.4	16.6	NS
2	18.2	17.9	18.3	18.1	NS
3	19.3	18.8	19.0	19.0	NS
4	20.5	19.9	19.7	20.1	NS
Mean	18.7	18.4	18.3	18.5	NS

Table 5. Leaf IVDMD per cutting of dryland and irrigated alfalfa subjected to exposed and sheltered wind conditions during the 1984 and 1985 growing season.

Year/ Cutting	Exposed		Sheltered		
	Dryland	Irrigated	Dryland	Irrigated	$LSD_{0.10}$
	%				
1984					
1	76.0	75.3	73.9	75.7	NS
2	77.3	77.1	77.2	77.7	NS
3	75.6	75.2	74.3	74.4	NS
4	73.0	72.3	74.6	74.5	NS
Mean	75.5	75.0	75.0	75.6	NS
1985					
1	78.3	78.9	78.6	78.2	NS
2	75.2	74.4	75.8	75.9	NS
3	75.1	73.9	75.4	75.4	NS
4	77.0	76.6	77.2	76.8	NS
Mean	76.4	75.9	76.7	76.6	NS

Table 6. Stem IVDMD per cutting of dryland and irrigated alfalfa subjected to exposed and sheltered wind conditions during the 1984 and 1985 growing season.

Year/ Cutting	Exposed		Sheltered		
	Dryland	Irrigated	Dryland	Irrigated	$LSD_{0.10}$
1984		%			
1	53.5	55.0	55.3	55.2	NS
2	52.2	52.0	51.2	52.4	NS
3	49.2	48.8	48.2	48.2	NS
4	53.5	54.0	53.4	54.1	NS
Mean	52.1	52.5	52.0	52.5	NS
1985					
1	59.2	59.7	60.2	59.0	NS
2	49.7	49.5	50.8	49.8	NS
3	53.1	53.9	53.4	52.2	NS
4	57.7	56.4	57.0	57.2	NS
Mean	54.9	54.9	55.3	54.6	NS

Table 7. Whole plant IVDMD per cutting of dryland and irrigated alfalfa subjected to exposed and sheltered wind conditions during the 1984 and 1985 growing season.

Year/ Cutting	Exposed		Sheltered		
	Dryland	Irrigated	Dryland	Irrigated	$LSD_{0.10}$
1984			%		
1	64.5	65.2	64.4	65.4	NS
2	66.8	67.2	66.6	67.1	NS
3	64.5	62.5	62.4	61.5	NS
4	64.5	64.0	64.8	65.1	NS
Mean	65.1	64.7	64.5	64.8	NS
1985					
1	67.7	68.4	68.0	67.2	NS
2	62.9	62.3	63.6	63.0	NS
3	64.3	63.3	64.0	63.1	NS
4	68.0	66.8	67.3	67.5	NS
Mean	65.7	65.2	65.7	65.2	NS

leaf, stem, and whole plant fractions. There were also no significant differences between sheltered and exposed quality parameters on a per cutting basis during either of the growing seasons. Trends in the data collected during 1984 and 1985 indicated that the influence of shelter on alfalfa crude protein plant fractions was small and ranged between ±3%. For IVDMD, the influence of shelter on alfalfa plant fractions was also small and ranged between ±1%.

The lack of significant differences between shelter and exposed alfalfa quality parameters may be attributed to the lack of significant shelter effects on environmental factors. Major environmental factors that influence alfalfa quality are air temperature and soil moisture. Previous studies have shown that warm versus cool air temperature conditions raise crude protein levels in alfalfa but lower its digestibility (Smith, 1969; Vough and Marten, 1971). At optimum soil moisture levels (50% available soil moisture), crude protein content and IVDMD may be increased more than at either higher or lower levels (Bezeau and Sonmer, 1964). In this study shelter had no significant influence on air temperature (Tables A.4 and A.5) or available soil moisture (Tables A.6 and A.7) resulting in unchanged levels of crude protein and IVDMD in leaf, stem, and whole plant fractions. These results are supported by small nonsignificant differences between shelter and exposed treatments observed for the leaf:stem ratio, a morphological indicator of alfalfa quality.

CONCLUSIONS

Shelterbelt wind reduction had no significant effect on alfalfa yield and quality under either dryland or irrigated moisture regimes at 7H. Even though the shelterbelts significantly reduced windspeed (approximately 40%) at a leeward distance of 7H, environmental parameters such as soil moisture and air temperature were unaffected. As a result, alfalfa growth parameters influencing yield and quality were not subjected to improved growing conditions and left unchanged by shelter. Therefore no relationship could be established between the effect of shelter on alfalfa yield and quality.

Similarities in alfalfa growth and yield between sheltered and exposed environments suggest that water stress from evapotransporation was not significantly reduced by the shelterbelts. Past literature has indicated that wind reduction by shelterbelts reduce the atmospheric evaporative demand resulting in lower evapotranspiration rates. This reduced evapotranspiration lessens the moisture stress on photosynthesizing leaves (Skidmore,1969). As a result, water use efficiency is improved and stomatal resistance is reduced to allow for greater photosynthetic opportunity and increased dry matter yields (Rosenberg 1975; Skidmore and Hagen, 1970). In both dryland and irrigated moisture regime treatments, available soil moisture and dry matter yields were not significantly increased by shelter. This is interpreted to mean that there was no improvement in water use efficiency or dry matter accumulation from lower evapotranspiration rates. Wind turbulence which is characteristic of dense shelterbelts may have prevented the reduction of evapotranspiration due to increased air mixing.

Turbulence may have also contributed to nonsignificant alfalfa growth and yield measurements in the sheltered treatments by preventing the reduction of mechanical wind stress. Reduction of wind induced bending, flexing, and shaking of plant parts has been reported to increase plant height and dry matter yield (Jaffe, 1980; Mitchell et al., 1975). Even though windspeed was significantly reduced by the shelterbelts, increased turbulence, if it occurred, may have nullified the beneficial effects of reducing mechanical wind stress.

Shelter has been shown to increase irrigated crop yields by reducing plant water stress during periods of strong evaporative demand (Rosenberg, 1975). In this study irrigated alfalfa yields were not increased in the sheltered treatments, however, there was a reduction in the amount of irrigation water needed to fill the soil profile to a specified moisture level. The difference in the amount of irrigation water applied to sheltered plots versus exposed plots was small (2.3 cm for 1984 and 2.2 cm for 1985) and probably due to only minor reductions in evapotranspiration by shelter. Perhaps in other sheltered situations where reduction of plant water stress is great enough to improve water use efficiency, significant savings in the amount of applied irrigation water may also be realized.

Differences between the data collected at 7H and visual observations of improved alfalfa growth at closer leeward distances to the shelterbelt warrant further study. Shelter effects on alfalfa growth, yield, and quality may be best represented by obtaining forage samples over a range of locations within the protection zone of the shelterbelt. Future research should concentrate on using shelterbelts of greater porosity (40 - 50%) that extend the protection zone further downwind from the belt and reduce wind turbulence, a negative characteristic of denser shelterbelts.

LITERATURE CITED

Aase, J.K., and F.H. Siddoway. 1974. Tall wheatgrass barriers and winter wheat response. Agr. Meteorol. 13:321-338.

Akimoto, Y., M. Itabaski, H. Saito, M. Sasaki. 1979. Studies on tobacco culture in subtropical conditions. 4. Effects of wind on rooting and growth of tobacco in its early stage. Jap. J. Crop Sci. 48:195-200.

Alcock, M.B., G. Harvey, and S.F. Tindsley. 1976. The effect of shelter on pasture production on hill land in North Wales. Fourth symposium on shelter research held at Warwick Univ., 1975. MAFF/ADAS.

Altena, H.J. 1978. (The effect of belts of trees on the production of adjoining grassland). Bedriifsont-wikkeling 9:751-753.

Andersen, P.C. 1943. (Shelterbelt Planting). Viborg: The Danish Health Society.

Association of Official Analytical Chemists. 1975. Official Methods of Analysis (12th ed.). Association of Official Agricultural Chemists, Washington, D.C.

Armbrust, D.V. 1982. Physiological responses to wind and sandblast damage by grain sorghum plants. Agron. J. 74:133-135.

Armbrust, D.V., G.M. Paulsen, and R. Ellis Jr. 1974. Physiological responses to wind and sandblast damaged winter wheat plants. Agron. J. 66:421-423.

Audus, L.J. 1935. Mechanical stimulation and respiration rate in the cherry laurel. New Phytol. 34:386-402.

Barker, G.L., J.L. Hatfield, and D.F. Wanjura. 1985. Cotton plant response to wind and water stress. Trans. ASAE 28:194-200.

Barnes, R.F., and C.H. Gordon. 1972. Feeding value and on-farm feeding. p. 601-630. In, C.H. Hanson (ed.), Alfalfa Science and Technology. Amer. Soc. Agron., Madison, WI.

Barnes, D.K., and C.C. Sheaffer. 1985. Alfalfa. p. 89-108. In, M.E. Heath, R.F. Barnes, and D.S. Metcalfe (eds.), Forages: The Science of Grassland Agriculture. Iowa State Univ. Press, Ames.

Bates, C.G. 1911. Windbreaks: Their influence and value. USDA For. Serv. Bull. 86.

Bates, C.G. 1944. The windbreak as a farm asset. USDA Farmers' Bull. 1405.

Batjer, D., R. Ness, J. Feise, and J. von Lucken. 1967. (Windbreaks in agriculture. 1. Results from investigations in the Weser Fens. 2. Hints for their practical use in the Fens). Akt. Frag. Landbaues SchrReihe Landw-Kammer Wesin-Ems. No. 2:119 and No. 3:520.

Baumgardt, B.R., and D. Smith. 1962. Changes in the estimated nutritive value of the herbage of alfalfa, medium red clover, ladino clover, and bromegrass due to stage of maturity and year. Wis. Agr. Exp. Sta. Res. Rep. 10.

Benkovits, K. 1955. (The influence of tree planting on the microclimate and grass yield of pastures). Erdesz. Kutatas. (Budapest) 3:3-18. [Forestry Abs. 18:497 (1957)].

Beyl, C.A., and C.A. Mitchell. 1983. Alteration of growth, exudation rate, and endogenous hormone profiles in mechanically dwarfed sunflower. J. Amer. Soc. Hort. Sci. 108:257-262.

Bezeau, L.M., and L.G. Sonmor. 1964. The influence of levels of irrigation on the nutritive value of alfalfa. Can. J. Plant Sci. 44:505-508.

Biro, R.L., and M.J. Jaffe. 1984. Thigmomorphogenesis: Ethylene evolution and its role in the changes observed in mechanically perturbed bean plants. Physiol. Plant. 62:289-296.

Biro, R.L., E.R. Hunt Jr., Y. Erner, and M.J. Jaffe. 1980. Thigmomorphogenesis: Decreased axial cell elongation and increased radial cell division in the internodes of mechanically perturbed or ethrel treated bean plants. Ann. Bot. 45:655-664.

Bodrov, V. 1936. The influence of shelterbelts on the microclimate of adjacent territories. J. For. 34:696-697.

Brown, K.W., and N.J. Rosenberg. 1970. Effect of windbreaks and soil water potential on stomatal diffusion resistance and photosynthetic rate of sugar beets (Beta vulgaris). Agron. J. 63:351-355.

Brown, K.W., and N.J. Rosenberg. 1971. Turbulent transport and energy balance as affected by a windbreak in an irrigated sugar beet (Beta vulgaris) field. Agron. J. 63:351-355.

Brown, K.W., and N.J. Rosenberg. 1972. Shelter effects on microclimate, growth and water use by irrigated sugar beets in the Great Plains. Agr. Meteorol. 9:241-263.

Caborn, J.M. 1957. Shelterbelts and microclimate. For. Comm. Bull. 29:1-35.

Caborn, J.M. 1960. The dependence of the shelter effect of shelterbelts on their structure. Proc. Fifth World For. Cong. 3:1662-1664.

Carlton, A.E., C.S. Cooper, R.H. Delaney, A.L. Dubbs, and R.F. Eslick. 1968. Growth and forage quality comparisons of sanfoin (Onobrychis viciaefolia Scop.) and alfalfa (Medicago sativa L.). Agron. J. 60:630-632.

Casperson, G. 1957. (Investigations of the influence of wind protection on local heat balance). Angew. Met. 2:339-351.

Chang, J.H. 1968. Climate and Agriculture. Aldine Publ. Co., Chicago.

Cittadini, J.C. 1955. (Lucerne growing in Patagonia, Argentina). Idia 96:30-32.

Collins, P.E. 1962. Shelterbelt influences. Proc. Internat. Semin. on Soil and Water Utilization, South Dakota State College, Brookings.

Cowett, E.R., and M.A. Sprague. 1962. Factors regulating tillering in alfalfa. Agron. J. 54:294-297.

Dekayos, E.F. 1972. Callose formation by bruising and heating of tomatoes and its prescence in processed products. J. Food Sci. 37:562-567.

Eisenhaur, D.E., P.E. Fischbach, W.L. Trimmer, and R.A. Krohn. 1979. Irrigation scheduling using soil moisture blocks in deep soil. Cooperative Ext. Serv., IANR, Univ. Nebraska, Lincoln. EC 79-723.

Elder, J.A., T.E. Beesley, and W.E. McKinzie. 1965. Soil Survey of Saunders County, Nebraska. USDA-SCS Series 1959, No.40.

Elliott, F.C., I.J. Johnson, and M.H. Schonhorst. 1972. Breeding for forage yield and quality. p. 319-333. In, C.H. Hanson (ed.), Alfalfa Science and Technology. Amer. Soc. of Agron., Madison, WI.

Faix, J.J. 1974. The effect of temperature and daylength on the quality of morphological components of three legumes. Ph.D. diss. Cornell Univ. (Diss. Abstr. 35:2021).

Farnworth, J. 1974. A preliminary study on the effect of shelter on alfalfa and Rhodes grass grown under irrigated arid zone conditions in Saudi Arabia. Publ. Joint Agr. Res. & Dev. Project, Univ. Coll. N. Wales, Bangor. Min. Agr. & Water, Saudi Arabia No. 35.

Frank, A.B., and W.O. Willis. 1978. Effect of winter and summer windbreaks on soil water gain and spring wheat yield. Soil Sci. Soc. Amer. J. 42:950-953.

Frank, A.B., D.G. Harris, and W.O. Willis. 1974. Windbreak influence on water relations, growth, and yield of soybeans. Crop Sci. 14:761-765.

Frank, A.B., D.G. Harris, and W.O. Willis. 1977a. Growth and yield of spring wheat as influenced by shelter and soil water. Agron. J. 69:903-906.

Frank, A.B., D.G. Harris, and W.O. Willis. 1977b. Plant water relationships of spring wheat as influenced by shelter and soil water. Agron. J. 69:906-910.

Fryrear, D.W., and J.D. Downes. 1975. Estimating seedling survival from wind erosion parameters. Trans. ASAE 18:888-891.

Gal, J., K. Tompa, and Z. Tihanyi. 1963. (Increase in field crop yields due to shelterbelts). Erdesz. Faipari Egyetem tud. Kozl., Sopron. No. 1-2:41-81.

Garay, A. 1981. Physical characteristics of soils of the Agricultural Meteorology Field Laboratory at Mead, Nebraska. Center for Agric. Meteor. & Climat. interdepartmental report. Univ. Nebraska. (unpubl.).

Garza, T.R., R.F. Barnes, G.O. Mott, and C.L. Rhykerd. 1965. Influence of light intensity, temperature and growing period on growth, chemical composition and digestibility of Culver and Tranverde alfalfa seedlings. Agron. J. 57:417-420.

George, E.J. 1971. Effect of tree windbreaks and slat barriers on wind velocity and crop yields. USDA-ARS Prod. Res. Rep. No. 121.

Godwin, H. 1935. The effect of handling on the respiration of cherry laurel leaves. New Phytol. 34:403-406.

Gorshenin, N.M., Y.D. Panfiloff, N.T. Godounoff, and others. 1934. (Improvement of farmland in the irrigated region of the Zavoljie). Goslestechnizdat, Moscow. [U.S. Forest Serv. Transl. 64. (1934)].

Grace, J. 1974. The effect of wind on grasses: I. Cuticular and stomatal transpiration. J. Exp. Bot. 25:542-551.

Grace, J. 1977. Plant Response to Wind. Academic Press, London.

Grace, J. 1987. Plant response to wind. In, J.R. Brandle and D.L. Hintz (eds.), Windbreaks. Elsevier Scientific Publ. Co., Amsterdam/Oxford/New York. (In press).

Grace, J., and C. Russell. 1977. The effect of wind on grasses. J. Exper. Bot. 28:268-278.

Grace, J., and C. Russell. 1982. The effect of wind and a reduced supply of water on the growth and water relations of *Festuca arundinacea* Schreb. Ann. Bot. 49:217-225.

Greig, J.K., N. Bokhara, D.V. Armbrust, and L.C. Anderson. 1974. Residual effects of wind and sand-blast damage on tomato plants at different stages of development. J. Amer. Soc. Hort. Sci. 99:530-534.

Groskopp, M.D., J.M. Sund, and J.T. Murdock. 1963. Irrigated alfalfa in central Wisconsin. Wisconsin Agr. Exp. Sta. Bull. 558.

Hagen, L.J., and E.L. Skidmore. 1971. Turbulent velocity fluctuations and vertical flow as affected by windbreak porosity. Trans. ASAE 14:634-637.

Hanks, R.J., J. Keller, V.P. Rasmussen, and G.D. Wilson. 1976. Line source sprinkler for continuous variable irrigation crop production studies. Soil Sci. Soc. Amer. Proc. 40:426-429.

Heisler, G.M., and D.R. DeWalle. 1987. Effects of windbreak structure on wind flow. In, J.R. Brandle and D.L. Hintz (eds.), Windbreaks. Elsevier Scientific Publ. Co., Amsterdam/Oxford/New York. (In press).

Heuchert, J.C., J.S. Marks, and C.A. Mitchell. 1983. Strengthening of tomato shoots by gyratory shaking. J. Amer. Soc. Hort. Sci. 108:801-805.

Hoy S.J. 1976. Forage yields, quality evaluations, regrowth characteristics, and root studies of cicer milkvetch (*Astragalus cicer*). Masters thesis, Univ. Nebraska, Lincoln.

Hsiao, T.C. 1973. Plant responses to water stress. Ann. Rev. Plant Physiol. 24:519-570.

Huberman, M., and M.J. Jaffe. 1981. Morphological changes of mechanically-perturbed or ethylene treated bean plants. Plant Physiol. Supplement 67:17.

Hunt, E.R. Jr., and M.J. Jaffe. 1980. Thigmomorphogenesis: The interaction of wind and temperature in the field on the growth of *Phaseolus vulgaris* L. Ann. Bot. 45:665-672.

Ignatiev, S.N. 1940. (Shelterbelts and the productivity of perennial grasses). Dokl. vsesoyuz-Akad. S-Kh. Nauk. 3:9-13. [Forestry Abstr. 3:47 (1941)].

Jaffe, M.J. 1973. Thigmomorphogenesis: The response of plant growth and development to mechanical stimulation. With special reference to *Bryonia diocia*. Planta 114:143-157.

Jaffe, M.J. 1976a. Thigmomorphogenesis: A detailed characterization of the response of beans (*Phaseolus vulgaris* L.) to mechanical stimulation. Z. Pflanzenphysiol. 77:437-453.

Jaffe, M.J. 1976b. Thigmomorphogenesis: Electrical resistance and mechanical correlates of the early events of growth retardation due to mechanical stimulation in beans. Z. Pflanzenphysiol. 78:24-32.

Jaffe, M.J. 1980. Morphogenetic responses of plants to mechanial stimuli or stress. Bio. Sci. 30:239-243.

Jaffe, M.J., and R. Biro. 1979. Thigmomorphogenesis: The effect of mechanical perturbation on the growth of plants, with special reference to anatomical changes, the role of ethylene, and interaction with other environmental stresses. p. 25-69. In, H. Mussell and R.C. Staples (eds.), Stress Physiology in Crop Plants. John Wiley and Sons, New York.

Jaffe, M.J., F.W. Telewski, and P. Cooke. 1984. Thigmomorphogenesis: On the mechanical properties of mechanically perturbed bean plants. Physiol. Plant. 62:73-78.

Jaffe, M.J., M. Huberman, J. Johnson, and F.W. Telewski. 1985. Thigmomophogenesis: The induction of callose formation and ethylene evolution by mechanical perturbation in bean stems. Physiol. Plant. 64:271-279.

Jensen, M. 1954. Shelter effect: Investigations into the aerodynamics of shelter and its effect on climate and crops. Danish Technical Press, Copenhagen.

Jensen, E.H., M.A. Massengale, and D.O. Chilcote. 1967. Environmental effects on growth and quality of alfalfa. Nevada Agr. Exp. Sta. Bull. T9.

Kahl, H. 1951. The influence of shaking on the structure and function of plant cytoplasm. Planta 39:346-376.

Kansas State University. 1978. Alfalfa production. Coop. Ext. Serv., Manhattan, Kansas. C-478.

Kilmer, V.J., O.L. Bennett, M.F. Stahly, and D.R. Timmons. 1960. Yield and mineral composition of eight forage species grown at four levels of soil moisture. Agron. J. 52:282-285.

Kimberlin, L.W., A.L. Hidelbaugh, A.R. Grunewald. 1977. The potential wind erosion problem in the United States. Trans. ASAE 14:634-637.

Larson, P.R. 1965. Stem formation of young Larix as influenced by wind and pruning. For. Sci. 11:412-424.

Lawson, M.P. 1977a. Climatic Atlas of Nebraska. University of Nebraska Press.

Lawson, M.P. 1977b. Agricultural Atlas of Nebraska. University of Nebraska Press.

Lemon, E. 1970. Gaseous exchange in crop stands. p. 117-137. In, J.D. Eastin, F.A. Haskins, C.Y. Sullivan, and C.H.M. van Bavel (eds.), Physiological Aspects of Crop Yield. Amer. Soc. Agron., Madison, WI.

Luckett, C.R., and T.J. Klopfenstein. 1970. Leaf-to-stem ratio and composition of alfalfa from five harvesting systems. J. Anim. Sci. 31:126-129.

Luckett, C.R., R.L. Ogden, T.J. Klopfenstein, and W.R. Kehr. 1967. Composition and digestibility of alfalfa leaf and stem fractions. J. Anim. Sci. 26:936.

Lyles, L., and N.P. Woodruff. 1960. Abrasive action of wind-blown soil on plant seedlings. Agron. J. 52:533-536.

Mackerron, D.K.L. 1976. Wind damage to the surface of strawberry leaves. Ann. Bot. 40:351-354.

Marshall, J.K. 1967. The effect of shelter on the productivity of grasslands and field crops. Field Crop Abstr. 20:1-14.

Marshall, J.K. 1974. Effects of shelter on growth of turnips and sugar beets. J. Appl. Ecol. 11:327-346.

Marten, G.C. 1970. Temperature as a determinat of quality of alfalfa harvested by bloom stage or age criteria. p. 506-509. In, Proc. 11th Internat. Grassl. Cong., Univ. Queensland Press, Brisbane, Australia.

Mascola, J.J., K.M. Barth, and H.A. Fribourg. 1971. Relation of stage of maturity and plant height to <u>in vitro</u> digestibility of Buffalo alfalfa. Tenn. Farm and Home Sci. 80:8-11.

McDougall, E.I. 1948. Studies on ruminants saliva. I. The composition and output of sheep's saliva. Biochem.J. 43:99-109.

McEwen, L.C., and D.R. Dietz. 1965. Shade effects on chemical composition of herbage in the Black Hills. J. Range Mgmt. 18:184-190.

McNaughton, K.G. 1987. Effects of windbreaks on turbulent transport and microclimate. In, J.R.Brandle and D.L. Hintz (eds.), Windbreaks. Elsevier Scientific Publ. Co., Amsterdam/Oxford/New York. (In press).

Meyer, J.H., W. Weir, L.G. Jones, and J.L. Hull. 1960. Effect of stage of maturity, dehydrating versus field-curing and pelleting on alfalfa hay quality as measured by lamb gains. J. Anim. Sci. 19:283.

Miller, D.R., N.J. Rosenberg, and W.T. Bagley. 1973. Soybean water use in the shelter of a slat fence windbreak. Agr. Meteorol. 11:405-418.

Miller, D.R., W.T. Bagley, and N.J. Rosenberg. 1974. Micro-climate modification with shelterbelts. J. Soil and Water Cons. 29:41-44.

Mitchell, C.A. 1977. Influence of mechanical stress on auxin-stimulated growth and excised pea stem sections. Physiol. Plant. 41:129-134.

Mitchell, C.A., H.C. Dostal, and T.M. Seipel. 1977. Dry weight reduction in mechanically-dwarfed tomato plants. J. Amer. Soc. Hort. Sci. 102:605-608.

Mitchell, C.A., C.J. Severson, J.A. Wott, and P.A. Hammer. 1975. Seismomorphogenic regulation of plant growth. J. Amer. Soc. Hort. Sci. 100:161-165.

Mullen, R.E., J.J. Vorst, H.E. Laborde, and C.L. Rhykerd. 1977. Yield and stand dynamics of Medicago sativa as influenced by seeding management. p. 789-791. In, Proc. 13th Internat. Grassl. Cong., Leipzig, GDR.

Neel, P.L., and R.W. Harris. 1972. Tree seedling growth: effects of shaking. Sci. 175:918-919.

National Oceanic and Atmospheric Administration. 1978. Climates of the states, Nebraska. p. 607-626. In, Climates of the States, Vol. 2. NOAA, Asheville, NC.

National Oceanic and Atmospheric Administration. 1984. Climatological data annual summary, Nebraska. NOAA, Environmental Data Service [etc.]. Vol.89 No.13. Asheville, NC.

National Oceanic and Atmospheric Administration. 1985. Climatological data annual summary, Nebraska. NOAA, Environmental Data Service [etc.]. Vol.90 No.13. Asheville, NC.

Nollette, G.R. 1983. Development of crop coefficient equations for irrigated soybeans using lysimeters in Nebraska. Masters thesis, Univ. Nebraska, Lincoln.

Ogbuehi, S.N., and J.R. Brandle. 1981. Influence of windbreak shelter on soybean production under rainfall conditions. Agron. J. 73:625-628.

Pappas, T., and C.A. Mitchell. 1983. Mechanical stress regulation of growth, transpiration, and photosynthetic productivity of Glycine Max Merr. C.V. Wells II. Plant Physiol. Supplement 72:62.

Peterson, H.B. 1972. Water relationships and irrigation. p. 469-480. In, C.H. Hanson (ed.), Alfalfa Science and Technology. Amer. Soc. of Agron., Madison, WI.

Pitcairn, C.E.R., and J. Grace. 1982. The effect of wind and a reduced supply of phosphorus and nitrogen on the growth and water relations of Festuca arundinacea Schreb. Ann. Bot. 49:649-660.

Pressman, E., M. Huberman, B. Aloni, and M.J. Jaffe. 1983. Thigmomorphogenesis: The effect of mechanical perturbation and ethrel on stem pithiness in tomato (Lycoperscicon esculentum Mill.) plants. Ann. Bot. 52:93-100.

Quayle, W.L. 1941. A shelterbelt increases hay yields. Wyo. Agr. Exp. Sta. Bull. 243.

Radcliffe, J.E. 1983. Grassland responses to shelter - a review. N. Z. J. Exp. Agric. 11:5-10.

Radke, J.K., and W.C. Burrows. 1970. Soybean plant response to temporary field windbreaks. Agron. J. 62:424-429.

Radke, J.K., and R.T. Hagstrom. 1974. Wind turbulence in a soybean field sheltered by four types of wind barriers. Agron. J. 66:273-278.

Read, R.A. 1964. Tree windbreaks for the central Great Plains. USDA For. Serv. Agric. Handbook 250.

Reddy, M.G., and G.N. Kulkarnie. 1978. The effect of shelterbelt on water use and yield of CSH-1 sorgham. Ann. Arid Zone 17:343-347.

Reid, J.T., W.K. Kennedy, K.L. Turk, S.T. Slack, G.W. Trimberger, and R.P. Murphy. 1959. Effect of growth stage, chemical composition and physical properties upon the nutritive value of forages. J. Dairy Sci. 42:567-571.

Rosenberg, N.J. 1966a. Microclimate, air mixing and physiological regulation of transpiration as influenced by wind shelter in an irrigated bean field. Agr. Meteorol. 3:197-224.

Rosenberg, N.J. 1966b. Influence of snow fence and corn windbreaks on microclimate and growth of irrigated sugar beets. Agron. J. 58:469-475.

Rosenberg, N.J. 1967. The influence and implications of windbreaks on agriculture in dry regions. p. 327-379. In, R.H. Shaw (ed.), Ground Level Climatology. Amer. Assoc. Adv. Sci.

Rosenberg, N.J. 1974. Microclimate: The Biological Environment. John Wiley & Sons, New York.

Rosenberg, N.J. 1975. Windbreak and shelter effects. p. 108-134. In, L.P. Smith (ed.), Progress in Biometeorology. Swets and Zeitlinger, Amsterdam.

Rosenberg, N.J. 1979. Windbreaks for reducing moisture stress. p. 394-408. In, B.J. Barfield and J.F. Gerber (eds.), Modification of the Aerial Environment of Plants. ASAE, St. Joseph, MI.

Rosenberg, N.J., D.W. Leecher, and R.E. Neild. 1967. Wind shelter-induced growth and physiological responses in irrigated snap beans. Proc. Amer. Soc. Hort. Sci. 90:169-179.

Russell, G., and J. Grace. 1978. The effect of wind on grasses. V. Leaf extension, diffusive conductance, and photosynthesis in the wind tunnel. J. Exp. Bot. 29:1249-1258.

Russell, G., and J. Grace. 1979a. The effect of windspeed on the growth of grasses. J. Appl. Ecol. 16:507-514.

Russell, G., and J. Grace. 1979b. The effect of shelter on the yield of grasses in southern Scotland. J. Appl. Ecol. 16:319-330.

Salisbury, F.B., and C.W. Ross. 1978. Plant Physiology. Wadsworth Publishing Co., Inc., Belmont, CA.

Saltveit, M.E. Jr., and R.A. Larson. 1983. Effect of mechanical stress and inhibitors of protein synthesis on leaf epinasty in mechanically stressed poinsettia plants. J. Amer. Soc. Hort. Sci. 108:253-257.

SAS Institute, Inc. 1982. SAS User's Guide: Statistics. SAS Institute, Inc., Cary, NC.

Shah, S.R.H. 1962. Studies on wind protection. Institute for Biological Field Research, Netherlands.

Shaposhnikov, A.P. 1946. (Growth and influence on crop yields of tree plantations for erosion control in the central forest steppe). Nauchny Otchet UNIALMI ZA 1941-1942, Sel/Khozgiz (Moscow) p. 82-90. [Forestry Abs. 9:174 (1947) No. 858].

Siddoway, F.H. 1970. Barriers for wind erosion control and water conservation. J. Soil and Water Cons. 25:180-184.

Skidmore, E.L. 1969. Modifying the microclimate with wind barriers. Great Plains Agric. Council Publ. 34:107-120.

Skidmore, E.L. 1976. Barrier induced microclimate and its influence on growth and yield of winter wheats. Great Plains Agric. Council Publ. 78:57-63.

Skidmore, E.L., and L.J. Hagen. 1970. Evaporation in sheltered areas as influenced by windbreak porosity. Agr. Meteorol. 7:363-374.

Skidmore, E.L., H.S. Jacobs, and L.J. Hagen. 1972. Microclimate modification by slat-fence windbreaks. Agron. J. 64:160-162.

Skidmore, E.L., L.J. Hagen, and I.D. Teare, 1975. Wind barriers most beneficial at intermediate stress. Crop Sci. 15:443-445.

Skidmore, E.L., L.J. Hagen, D.G. Naylor, and I.D. Teare. 1974. Winter wheat response to barrier-induced microclimate. Agron. J. 66:501-505.

Smith, D. 1969. Influence of temperature on yield and chemical composition of Vernal alfalfa at first flower. Agron. J. 61:470-472.

Smith,D. 1970. Yield and chemical composition of leaves and stems of alfalfa at intervals up the shoots. J. Agr. Food Chem. 18:652-656.

Snaydon, R.W. 1972. The effect of total water supply and frequency of application upon lucerne. II. Chemical composition. Aust. J. Agric. Res. 23:253-256.

Steel, R.G., and J.H. Torrie. 1980. Principles and Prodedures of Statistics: A Biometrical Approach. Second edition. McGraw-Hill Book Co., New York.

Steubing, L. 1954. (Experimental studies on the modification of site factors by shelterbelts). Oikos 4:118-147. [Forestry Abs. 16:65-66 (1955)].

Stoeckler, J.H. 1962. Shelterbelt influence on Great Plains field environment and crops. USDA Prod. Res. Report No. 62.

Stoeckler, J.H. 1965. The design of shelterbelts in relation to crop yield improvement. World Crops 17:27-32.

Sturrock, J.W. 1970. Progress in shelter research. Farm For. 12:62-78.

Sturrock, J.W. 1975. Wind effects and their amelioration on crop production. p. 283-314. In, U.S. Gupta (ed.) Physiological Aspects of Dryland Farming. Oxford and IBH Publ. Co., New Delhi.

Sturrock, J.W. 1981. Shelter boosts crop yield by 35 per cent: also prevents lodging. N. Z. J. Agr. 143:18-19.

Sturrock, J.W. 1984. Shelter research needs in relation to primary production: The report of the National Shelter Working Party. CRD/DSIR, Water & Soil Misc. Publ. No. 59.

Takahashi, H., and M.J. Jaffe, 1984, Thigmomorphogenesis: The relationship of mechanical perturbation to elicitor-like activity and ethylene production. Physiol. Plant. 61:405-411.

Terry, R.A., and J.M.A. Tilley. 1964. The digestibility of leaves and stems of perennial ryegrass, cocksfoot, timothy, tall fescue, lucerne, and sainfoin as measured by an in vitro procedure. J. Brit. Grassl. Soc. 19:363-372.

Thompson, J.R. 1974. The effect of wind on grasses: II. Mechanical damage in Festuca arundinacea Schreb. J. Exp. Bot. 25:965-972.

Tilley, J.M.A., and R.A. Terry. 1963. A two-stage technique for the in vitro digestion of forage crops. J. Brit. Grassl. Soc. 18:104-111.

Todd, G.W., D.L. Chadwick, and T. Sing-Dao. 1972. Effect of wind on plant respiration. Physiol. Plant. 27:342-346.

Trenk, F.B., 1948. Influence of planted tree belt in plainfield sand on erosion control and moisture conservation. Iowa State College J. Sci. 22:449-461. [Forestry Abs. 10:341 (1949)].

Turgeon, R., and J.A. Webb. 1971. Growth inhibition by mechanical stress. Sci. 174:961-962.

Ujah, J.E., and K.B. Adeoye, 1984. Effects of shelterbelts in the sudan savanna zone of Nigeria on microclimate and yield of millet. Agr. For. Meteorol. 33:99-107.

van der Linde, P.J. 1962. Trees outside the forest. Forest influences. FAO Forestry Prod. Stud. 15:141-208.

van Eimern, J. 1966. Protection of soils, plants and animals against wind. Proc. World Meteorol. Org. Semin., Australia. Agr. Meteor. 2:621-638.

van Eimern, J., R. Karschon, L.A. Razumova, and G.W. Robertson. 1964. Windbreaks and Shelterbelts. World Meteorol. Org. Tech. Note No. 59.

Venning, F.D. 1949. Stimulation by wind motion of collenchyma formation in celery petioles. Bot. Gaz. 110:511-514.

Victor, T.S., and L.N. Vanderhoef. 1975. Mechanical inhibition of hypocotyl elongation induces radial enlargement. Plant Physiol. 56:845-846.

Vough, L.R., and G.C. Marten. 1971. Influence of soil moisture and ambient temperature on yield and quality of alfalfa forage. Agron. J. 63:40-42.

Wadsworth, R.M. 1959. An optimum wind speed for plant growth. Ann. Bot. 23:195-199.

Wadsworth, R.M. 1960. The effect of artificial wind on the growth rate of plants in water culture. Ann. Bot. 24:200-210.

Whitehead, F.H. 1962. Experimental studies of the effect of wind on plant growth and anatomy. II. Helianthus annuus. New Phytol. 67:59-62.

Wilson, J. 1984. Microscopic features of wind damage to leaves of *Acer pseudoplatanus* L. Ann. Bot. 53:73-82.

Woodruff, N.P., R.A. Read, and W.S. Chepil. 1959. Influence of a field windbreak on summer wind movement and air temperature. Kansas Agr. Exp. Sta. Tech. Bull. No. 100.

Younie, D., and I.B. Ruxton. 1977. The effect of shelter on yield and composition of oats and barley grown for forage in Saudi Arabia. Publ. Joint Agr. Res. and Dev. project, Univ. Coll. of N. Wales, Min. Agric. & Water, Saudi Arabia No. 90.

APPENDIX A: DATA ANALYSIS

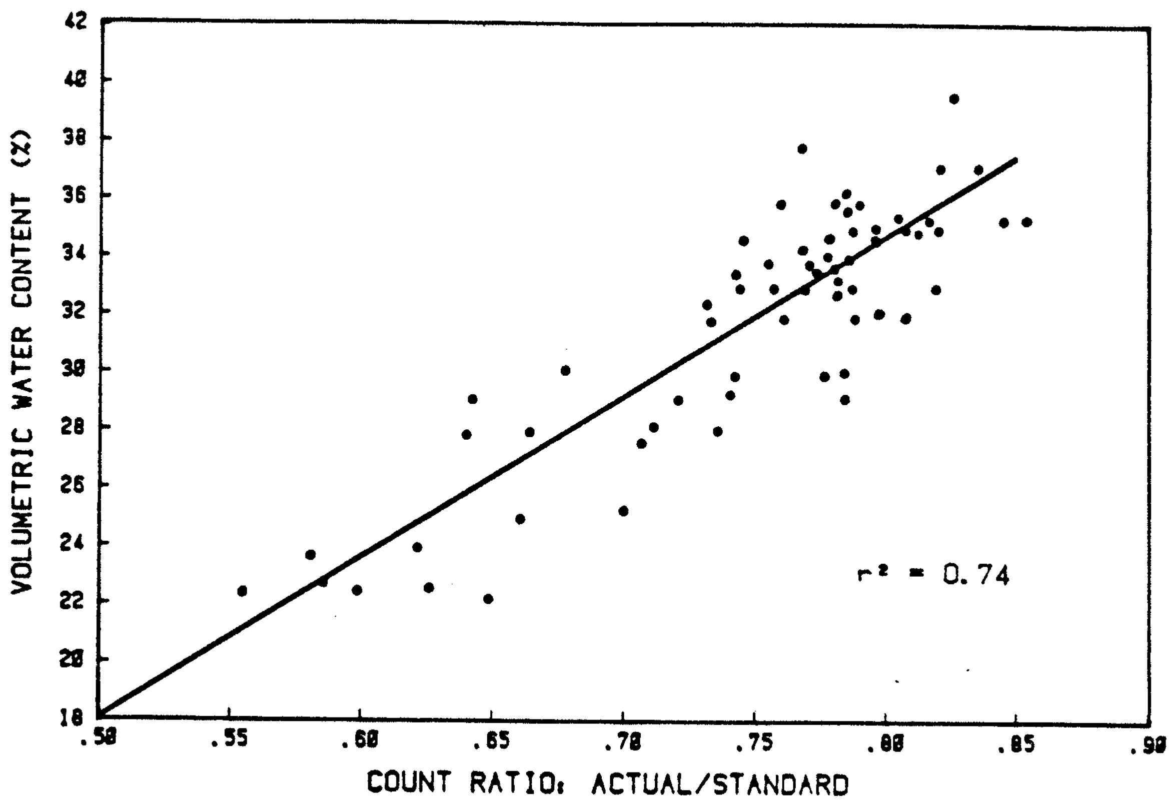

Figure A.1. Neutron probe calibration curve for the shelterbelt study.

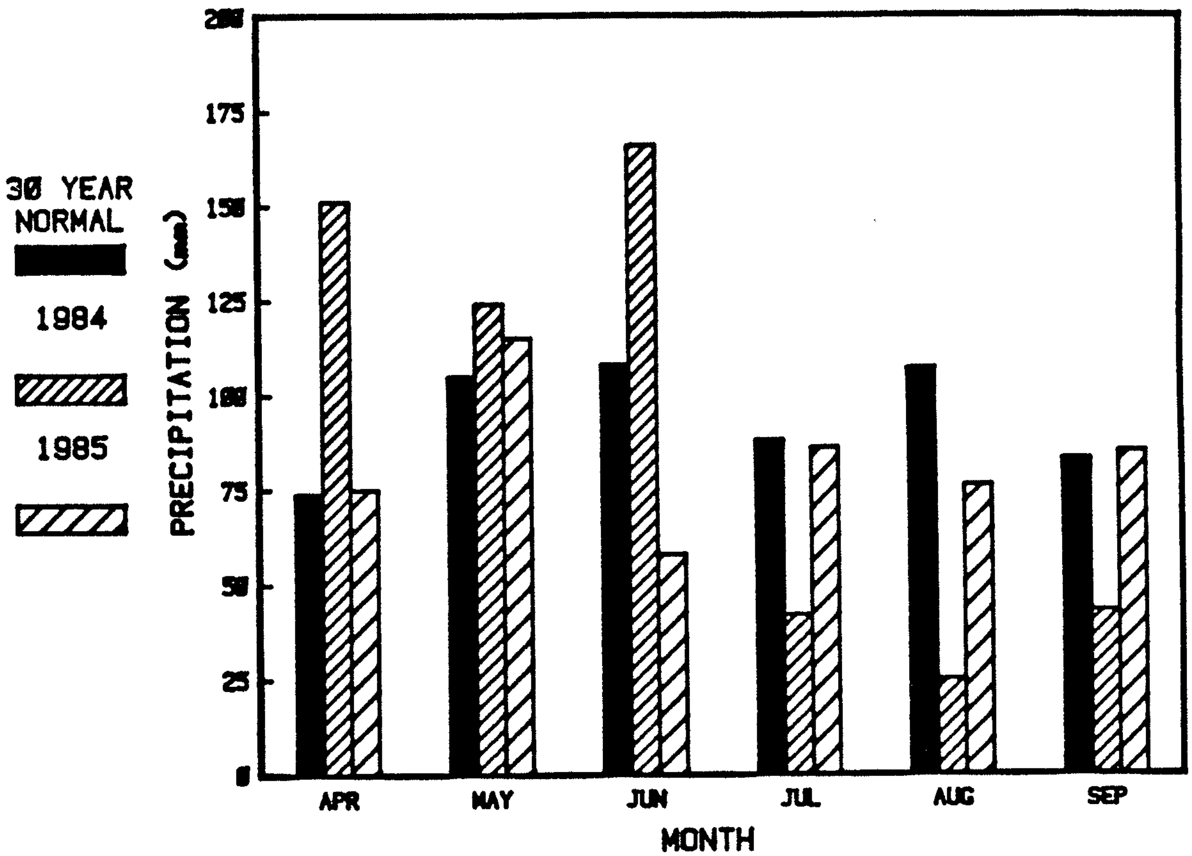

Figure A.2. Monthly precipitation levels for 1984, 1985, and 30 year normal, April through September (NOAA, 1984; 1985).

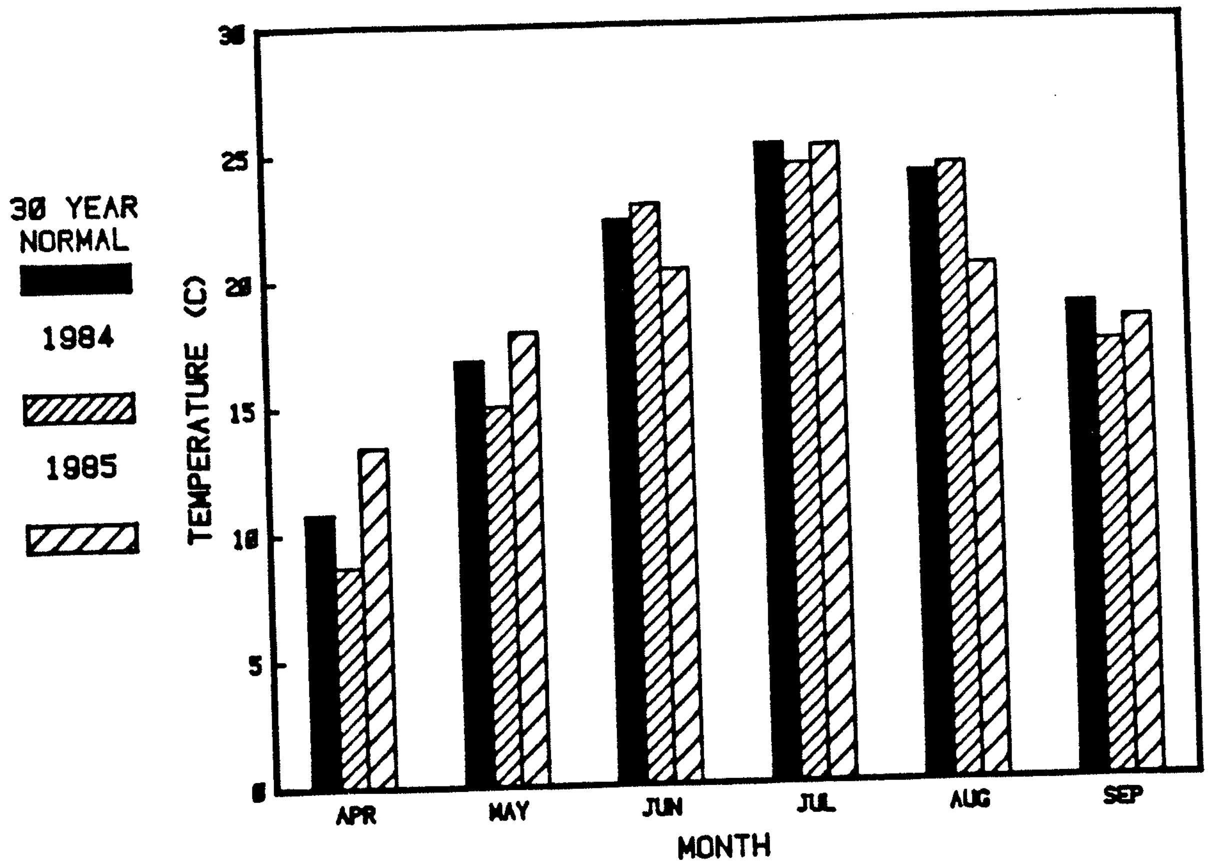

Figure A.3. Monthly average air temperatures for 1984, 1985, and 30 year normal, April through September (NOAA, 1984; 1985).

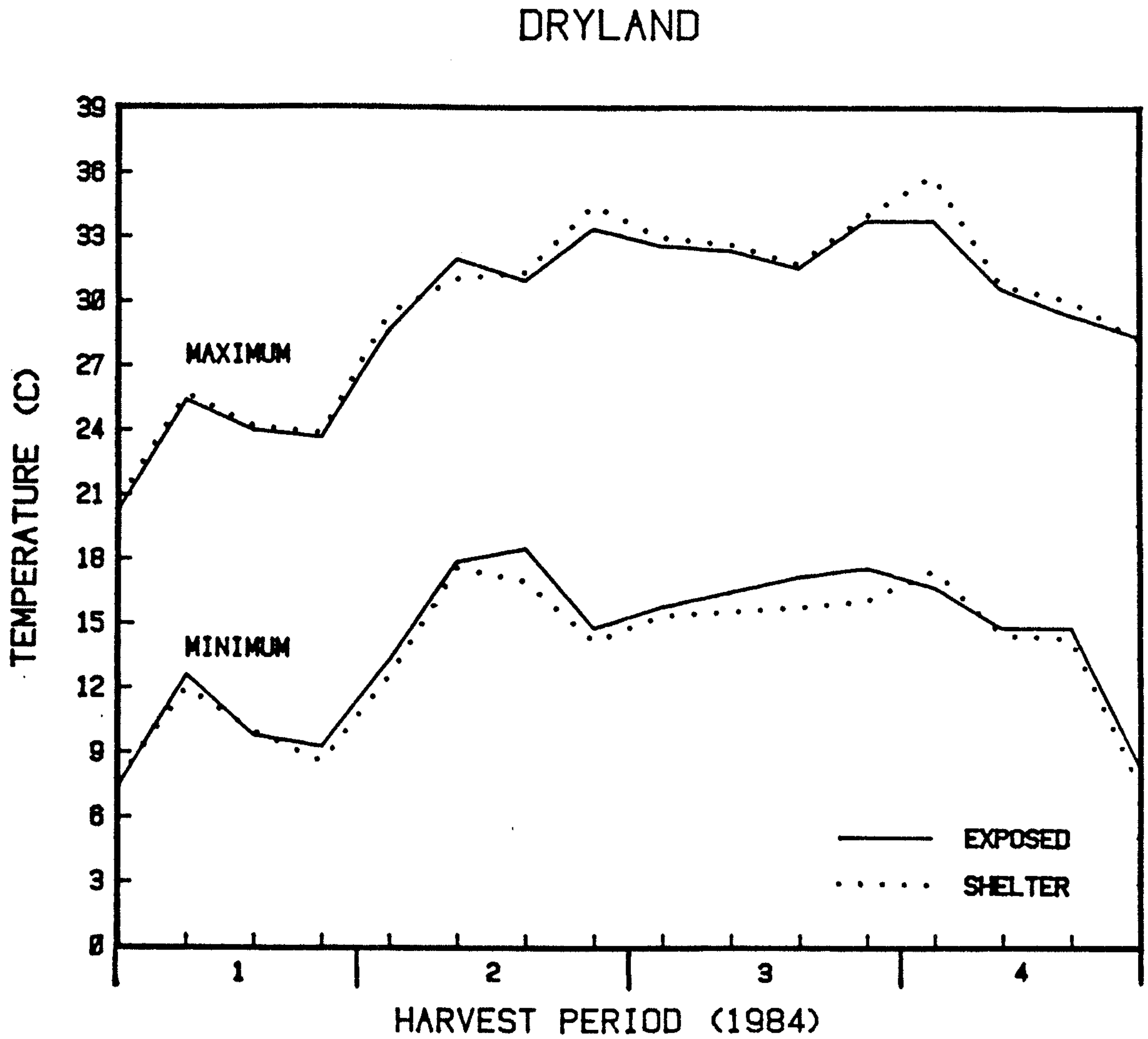

Figure A.4. Maximum and minimum air temperatures in shelter and exposed dryland plots over the 1984 growing season.

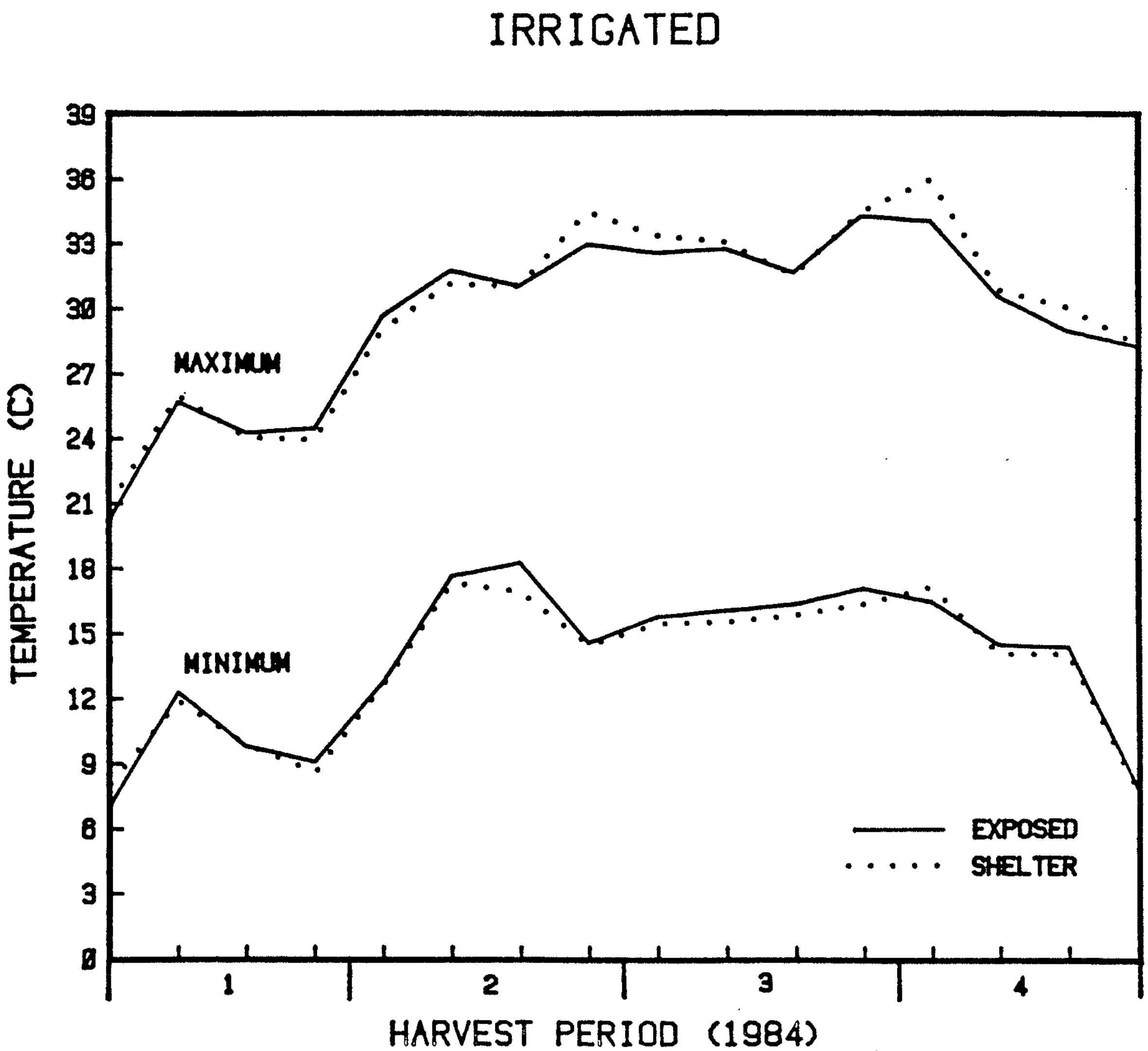

Figure A.5. Maximum and minimum air temperatures in shelter and exposed irrigated plots over the 1984 growing season.

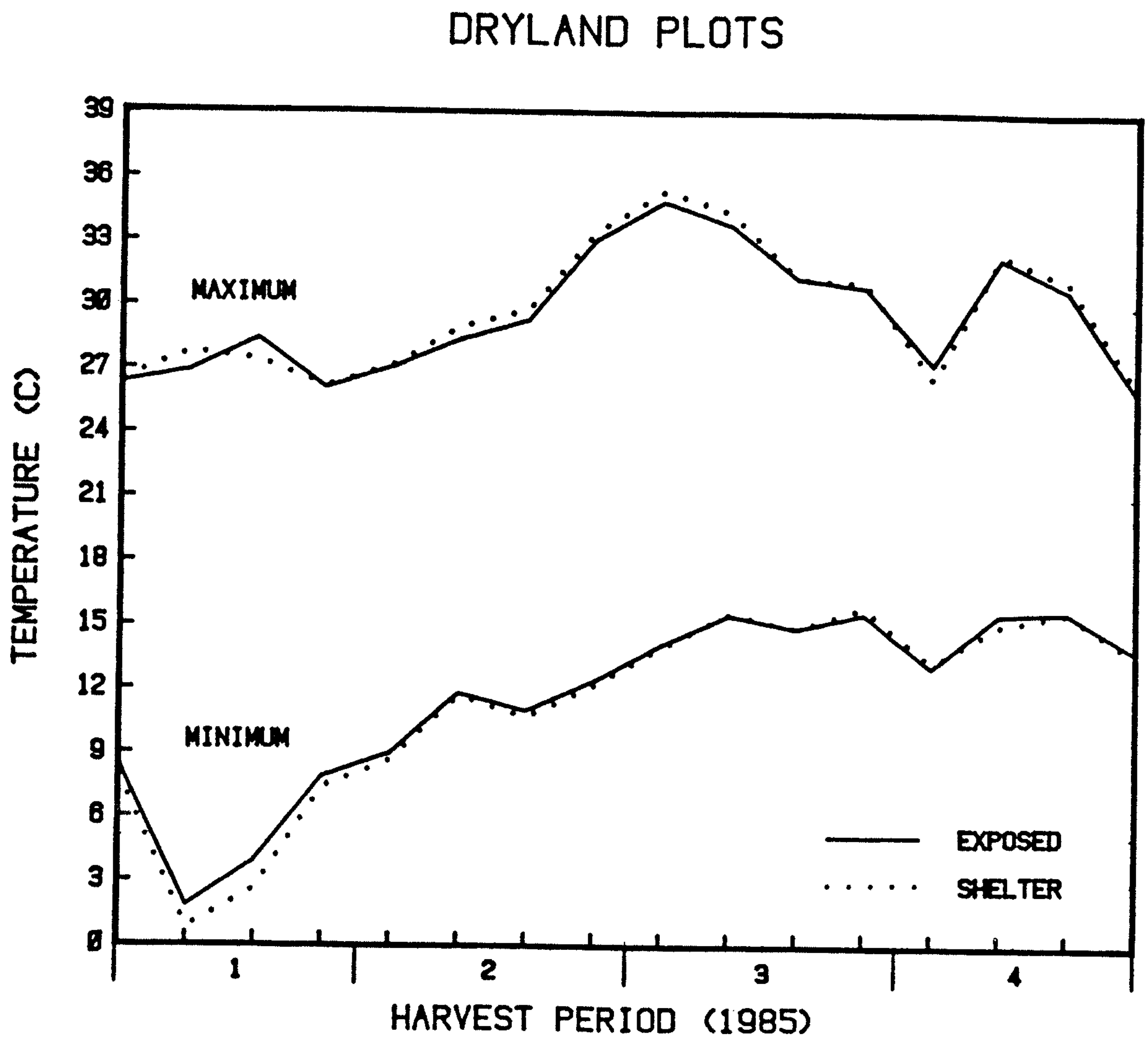

Figure A.6. Maximum and minimum air temperatures in shelter and exposed dryland plots over the 1985 growing season.

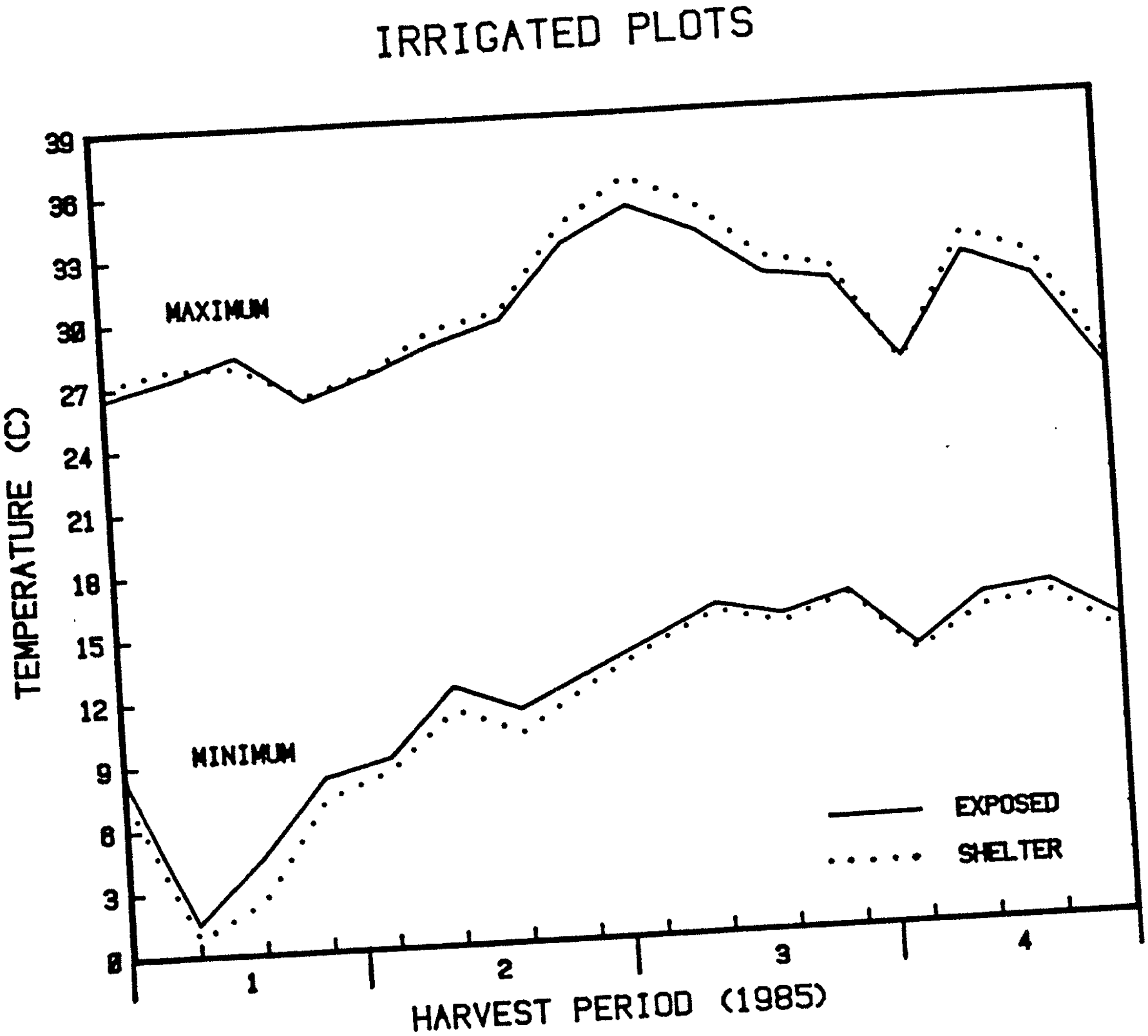

Figure A.7. Maximum and minimum air temperatures in shelter and exposed irrigated plots over the 1985 growing season.

Table A.1. Alfalfa harvest dates for each cutting during the 1984 and 1985 growing season.

Year	Cutting	Harvest Date
1984	1	June 6
	2	July 2
	3	August 6
	4	September 21
1985	1	May 19
	2	July 5
	3	August 8
	4	September 19

Table A.2. Mean monthly precipitation and air temperatures for the 1984 and 1985 growing season at the Agricultural Research and Development Center, Mead, Nebraska.

Month	Precipitation		
	1984	1985	*Normal
	mm		
April	151	75	74
May	124	115	105
June	166	58	108
July	42	86	88
August	25	76	107
September	43	85	83
Total	551	495	565

Month	Air Temperature		
	1984	1985	*Normal
	^{o}C		
April	8.7	13.4	10.8
May	15.0	17.9	16.8
June	22.9	20.3	22.3
July	24.4	25.1	25.2
August	24.3	20.3	24.0
September	17.2	18.1	18.7
Average	18.8	19.2	19.6

* Precipitation and air temperature normals are based on a 30 year period (1951-1980) recorded at Ashland, Nebraska (NOAA, 1985).

Table A.3. Windrun amount and reduction in sheltered and exposed alfalfa plots during the 1984 and 1985 growing season.

Year/ Cutting	Windrun			
	Exposed	Sheltered	Reduction	$LSD_{0.05}$
1984	km		%	
1	861	525	39.1	122
2	877	518	40.9	122
3	1175	686	41.6	122
4	1528	890	41.7	122
Mean	1111	655	41.0	117
1985				
1	2227	1290	42.1	245
2	2096	1307	37.6	245
3	1113	671	39.7	245
4	1396	811	41.9	245
Mean	1708	1019	40.3	223

Table A.4. Maximum air temperatures per cutting of dryland and irrigated alfalfa subjected to exposed and sheltered wind conditions during the 1984 and 1985 growing season.

Year/ Cutting	Exposed		Sheltered		
	Dryland	Irrigated	Dryland	Irrigated	$LSD_{0.10}$
1984		^{o}C			
1	23.3	23.7	23.6	23.7	NS
2	31.3	31.4	31.6	31.5	NS
3	32.4	32.8	32.9	33.2	NS
4	30.5	30.5	31.3	31.3	NS
Mean	29.4	29.6	29.8	29.9	NS
1985					
1	26.9	27.0	26.9	27.3	NS
2	29.5	29.5	29.9	30.0	NS
3	32.7	32.4	33.1	33.4	NS
4	29.1	28.7	29.2	29.3	NS
Mean	29.5	29.4	29.8	30.0	NS

Table A.5. Minimum air temperatures per cutting of dryland and irrigated alfalfa subjected to exposed and sheltered wind conditions during the 1984 and 1985 growing season.

	Exposed		Sheltered		
Year/ Cutting	Dryland	Irrigated	Dryland	Irrigated	$LSD_{0.10}$
1984		°C			
1	9.8	9.6	9.6	9.6	NS
2	16.1	15.8	15.3	15.4	NS
3	16.9	16.3	15.7	15.8	NS
4	13.7	13.3	13.4	13.3	NS
Mean	14.1	13.8	13.5	13.5	NS
1985					
1	5.5	5.6	4.7	4.4	NS
2	11.0	11.2	10.8	10.3	NS
3	15.0	15.0	15.1	14.7	NS
4	14.6	14.6	14.4	14.0	NS
Mean	11.5	11.6	11.2	10.9	NS

Table A.6. Available soil moisture measured to a depth of 150 cm at different dates during the 1984 growing season in dryland and irrigated alfalfa plots subjected to exposed and sheltered wind conditions.

	Exposed		Sheltered		
Date	Dryland	Irrigated	Dryland	Irrigated	$LSD_{0.10}$
	cm				
6/01	23.7	23.8	25.3	24.4	NS
6/08	23.5	23.3	25.7	24.6	NS
6/15	23.9	24.1	26.0	25.1	NS
6/26	22.1	22.4	24.6	23.6	NS
7/13	18.4	18.7	19.0	19.6	NS
7/20	14.5	19.6	17.1	21.3	NS
7/27	12.1	19.0	15.3	20.5	NS
8/03	8.9	18.1	12.0	20.1	NS
9/23	5.9	14.0	8.5	16.1	NS
Mean	17.0	20.7	19.3	21.7	NS

Table A.7. Available soil moisture measured to a depth of 150 cm at different dates during the 1985 growing season in dryland and irrigated alfalfa plots subjected to exposed and sheltered wind conditions.

	Exposed		Sheltered		
Date	Dryland	Irrigated	Dryland	Irrigated	$LSD_{0.10}$
	cm				
4/17	20.3	22.3	24.2	24.5	NS
5/02	21.0	23.3	24.7	25.0	NS
5/09	19.5	21.5	22.6	22.7	NS
5/25	20.4	22.1	22.3	23.3	NS
6/03	20.2	21.8	22.7	23.2	NS
6/13	18.1	20.1	22.0	21.9	NS
6/22	15.7	17.5	19.8	19.8	NS
7/11	12.1	12.5	14.5	15.4	NS
7/27	11.1	18.7	14.7	19.4	NS
8/07	10.0	16.7	13.3	19.4	NS
8/16	10.4	17.0	13.9	18.1	NS
8/26	10.3	16.4	13.9	17.8	NS
9/06	9.6	14.4	13.0	16.0	NS
Mean	15.3	18.8	18.6	20.4	NS

Table A.8. Average amount of irrigation water applied to alfalfa plots during the 1984 and 1985 growing season.

Year/ Application	Date	Exposed	Sheltered	Difference
1984			cm	
1	7/16	6.3	6.0	0.3
2	7/25	2.9	2.4	0.5
3	8/9	3.5	3.2	0.3
4	8/19	3.3	2.9	0.4
5	8/30	3.6	2.8	0.8
Total		19.6	17.3	2.3
1985				
1	7/13	9.2	7.0	2.2
Total		9.2	7.0	2.2

Table A.9. Plant height per cutting of dryland and irrigated alfalfa subjected to exposed and sheltered wind conditions during the 1984 and 1985 growing season.

Year/ Cutting	Exposed		Sheltered		
	Dryland	Irrigated	Dryland	Irrigated	$LSD_{0.10}$
1984		cm			
1	72.5	69.4	71.8	71.7	NS
2	50.3	50.9	48.3	43.8	NS
3	55.6	67.5	61.4	70.7	NS
4	49.3	56.1	51.8	59.9	NS
Mean	56.9	61.0	58.3	61.5	NS
1985					
1	80.9	83.6	85.8	86.6	NS
2	69.3	72.6	69.3	71.2	NS
3	70.6	77.7	73.7	76.7	NS
4	60.2	64.7	67.0	65.4	NS
Mean	70.3	74.6	73.9	75.0	NS

Table A.10. Leaf:stem ratio per cutting of dryland and irrigated alfalfa subjected to exposed and sheltered wind conditions during the 1984 and 1985 growing season.

Year/ Cutting	Exposed		Sheltered		
	Dryland	Irrigated	Dryland	Irrigated	$LSD_{0.10}$
1984	leaf/stem				
1	1.01	1.01	0.96	0.99	NS
2	1.40	1.55	1.49	1.39	NS
3	1.39	1.09	1.21	1.04	NS
4	1.33	1.23	1.28	1.16	NS
Mean	1.28	1.29	1.23	1.15	NS
1985					
1	0.80	0.83	0.75	0.76	NS
2	1.07	1.07	1.04	1.02	NS
3	1.03	0.88	0.98	0.90	NS
4	1.15	1.08	1.05	1.11	NS
Mean	1.01	0.97	0.95	0.95	NS

Table A.11. Plant density per cutting of dryland and irrigated alfalfa subjected to exposed and sheltered wind conditions during the 1984 and 1985 growing season.

Year/ Cutting	Exposed		Sheltered		
	Dryland	Irrigated	Dryland	Irrigated	$LSD_{0.10}$
1984	plants/m^2				
1	58.7	56.7	65.7	68.3	NS
2	57.0	55.3	63.7	65.0	NS
3	57.0	55.3	63.7	65.0	NS
4	57.0	54.0	63.0	65.0	NS
Mean	57.4	55.3	64.0	65.8	NS
1985					
1	56.7	52.0	60.0	59.7	NS
2	55.3	49.7	58.7	59.0	NS
3	53.3	46.3	55.0	56.3	NS
4	51.0	44.3	51.0	49.3	NS
Mean	54.1	48.1	56.2	56.1	NS

Table A.12. Stem density per cutting of dryland and irrigated alfalfa subjected to exposed and sheltered wind conditions during the 1984 and 1985 growing season.

Year/ Cutting	Exposed		Sheltered		
	Dryland	Irrigated	Dryland	Irrigated	$LSD_{0.10}$
1984	stems/m^2				
1	425.7	437.7	511.3	495.7	NS
2	597.0	586.0	628.0	613.3	NS
3	697.0	654.0	657.3	636.3	NS
4	598.0	598.0	710.7	614.0	NS
Mean	579.4	568.9	626.8	589.3	NS
1985					
1	466.0	453.3	516.3	529.7	NS
2	575.7	543.3	616.3	621.0	NS
3	596.3	517.7	638.0	618.0	NS
4	526.0	446.0	554.7	535.3	NS
Mean	541.0	490.1	581.3	576.0	NS

Table A.13. Stems per plant per cutting of dryland and irrigated alfalfa subjected to exposed and sheltered wind conditions during the 1984 and 1985 growing season.

Year/ Cutting	Exposed		Sheltered		
	Dryland	Irrigated	Dryland	Irrigated	$LSD_{0.10}$
1984	stems/plant				
1	7.4	7.8	8.0	7.4	NS
2	10.7	10.6	10.3	9.7	NS
3	12.8	11.9	10.6	10.0	NS
4	10.8	11.2	11.6	9.6	NS
Mean	10.4	10.4	10.1	9.2	NS
1985					
1	8.5	8.8	8.7	9.1	NS
2	10.8	10.9	10.8	10.8	NS
3	11.5	11.2	11.9	11.1	NS
4	10.6	10.2	11.2	11.3	NS
Mean	10.3	10.3	10.7	10.6	NS

Table A.14. Yield per cutting of dryland and irrigated alfalfa subjected to exposed and sheltered wind conditions during the 1984 and 1985 growing season.

Year/ Cutting	Exposed		Sheltered		
	Dryland	Irrigated	Dryland	Irrigated	$LSD_{0.10}$
1984	Mg/ha				
1	4.03	4.16	4.74	4.52	NS
2	2.93	3.12	3.35	3.13	NS
3	3.62	4.74	3.66	4.32	NS
4	2.83	3.13	2.88	3.11	NS
Total	13.41	15.15	14.63	15.08	NS
1985					
1	5.01	4.80	5.04	5.14	NS
2	4.18	4.39	4.00	4.14	NS
3	3.03	3.17	2.97	3.11	NS
4	2.21	2.49	2.34	2.39	NS
Total	14.43	14.85	14.35	14.78	NS

APPENDIX B: ANOVA TABLES

Table B.1. Analysis of variance for response of windrun to treatments obtained over 3 cuttings during the 1984 and 1985 growing season.

Source of Variation	DF	1984 Mean Square	1984 P>F	1985 Mean Square	1985 P>F
Wind Condition	1	557729.64	0.0001	1861395.41	0.0001
Replication(Wind)	6	7022.97		25597.45	
Cutting	2	87574.93	0.0001	1118498.30	0.0001
Cut*Wind	2	8141.87	0.0001	77796.76	0.0001
Cut*Rep(Wind)	12	302.44		2292.87	
Subsample Error	72				
Total	95				
C.V. (%)		14.0		14.3	

Table B.2. Analysis of variance for response of maximum air temperature to treatments obtained over 4 cuttings during the 1984 and 1985 growing season.

Source of Variation	DF	1984 Mean Square	1984 P>F	1985 Mean Square	1985 P>F
Wind Condition	1	9.73	0.2143	11.26	0.0281
Replication(Wind)	6	5.04		1.36	
Moisture Regime	1	1.25	0.0945	0.28	0.7229
Mois*Wind	1	0.21	0.4493	2.50	0.3110
Mois*Rep(Wind)	6	0.32		2.04	
Cutting	3	1100.09	0.0001	377.46	0.0001
Cut*Wind	3	1.17	0.0527	0.65	0.3341
Cut*Rep(Wind)	18	0.38		0.53	
Cut*Mois	3	0.52	0.1614	0.46	0.0891
Cut*Wind*Mois	3	0.13	0.6999	0.26	0.2683
Cut*Mois*Rep(Wind)	18	0.27		0.18	
Subsample Error	192				
Total	255				
C.V. (%)		0.1		1.7	

Table B.3. Analysis of variance for response of minimum air temperature to treatments obtained over 4 cuttings during the 1984 and 1985 growing season.

Source of Variation	DF	1984 Mean Square	1984 P>F	1985 Mean Square	1985 P>F
Wind Condition	1	11.73	0.0072	16.81	0.0001
Replication(Wind)	6	0.74		0.15	
Moisture Regime	1	1.89	0.2940	1.66	0.2591
Mois*Wind	1	1.79	0.3062	3.38	0.1256
Mois*Rep(Wind)	6	1.43		1.07	
Cutting	3	567.87	0.0001	1337.62	0.0001
Cut*Wind	3	2.34	0.0001	2.55	0.0003
Cut*Rep(Wind)	18	0.14		0.24	
Cut*Mois	3	0.12	0.5608	0.05	0.9016
Cut*Wind*Mois	3	0.16	0.4427	0.04	0.9340
Cut*Mois*Rep(Wind)	18	0.17		0.27	
Subsample Error	192				
Total	255				
C.V. (%)		4.4		4.6	

Table B.4. Analysis of variance for response of available soil moisture to treatments obtained over 4 cuttings during the 1984 and 1985 growing season.

Source of Variation	DF	1984 Mean Square	1984 P>F	1985 Mean Square	1985 P>F
Wind Condition	1	300.55	0.0934	938.20	0.0388
Replication(Wind)	6	75.73		135.10	
Moisture Regime	1	1020.13	0.0019	1101.77	0.0439
Mois*Wind	1	45.45	0.3085	109.80	0.4528
Mois*Rep(Wind)	6	36.73		170.43	
Cutting	3	1058.09	0.0001	732.01	0.0001
Cut*Wind	3	2.55	0.5925	2.48	0.7863
Cut*Rep(Wind)	18	3.13		3.78	
Cut*Mois	3	206.08	0.0001	57.00	0.0001
Cut*Wind*Mois	3	4.89	0.1679	2.16	0.6326
Cut*Mois*Rep(Wind)	18	3.17		2.65	
Subsample Error	128				
Total	191				
C.V. (%)		15.4		35.7	

Table B.5. Analysis of variance for response of alfalfa height to treatments obtained over 4 cuttings during the 1984 and 1985 growing season.

		1984		1985	
Source of Variation	DF	Mean Square	P>F	Mean Square	P>F
Wind Condition	1	45.73	0.3157	192.80	0.0007
Replication(Wind)	6	38.16		4.87	
Moisture Regime	1	628.94	0.0091	350.46	0.0028
Mois*Wind	1	9.50	0.6580	136.01	0.0227
Mois*Rep(Wind)	6	43.96		14.69	
Cutting	3	4974.56	0.0001	3340.83	0.0001
Cut*Wind	3	192.37	0.0003	60.60	0.0690
Cut*Rep(Wind)	18	18.41		21.58	
Cut*Mois	3	490.61	0.0002	31.83	0.1233
Cut*Wind*Mois	3	40.48	0.4210	14.30	0.4208
Cut*Mois*Rep(Wind)	18	41.01		14.47	
Subsample Error	128				
Total	191				
C.V. (%)		5.6		2.6	

Table B.6. Analysis of variance for response of alfalfa leaf:stem ratio to treatments obtained over 4 cuttings during the 1984 and 1985 growing season.

Source of Variation	DF	1984 Mean Square	1984 P>F	1985 Mean Square	1985 P>F
Wind Condition	1	0.19	0.2041	0.08	0.0223
Replication(Wind)	6	0.09		0.01	
Moisture Regime	1	0.28	0.0081	0.04	0.1224
Mois*Wind	1	0.01	0.5975	0.02	0.2484
Mois*Rep(Wind)	6	0.02		0.01	
Cutting	3	1.77	0.0001	0.92	0.0001
Cut*Wind	3	0.02	0.6197	0.03	0.4543
Cut*Rep(Wind)	18	0.03		0.04	
Cut*Mois	3	0.19	0.0001	0.02	0.0073
Cut*Wind*Mois	3	0.08	0.0079	0.01	0.1049
Cut*Mois*Rep(Wind)	18	0.02		0.01	
Subsample Error	128				
Total	191				
C.V. (%)		5.8		5.2	

Table B.7. Analysis of variance for response of alfalfa plant density to treatments obtained over 4 cuttings during the 1984 and 1985 growing season.

Source of Variation	DF	1984 Mean Square	1984 P>F	1985 Mean Square	1985 P>F
Wind Condition	1	3502.08	0.1737	1220.08	0.3002
Replication(Wind)	6	1469.97		949.31	
Moisture Regime	1	0.75	0.9537	444.08	0.1929
Mois*Wind	1	184.08	0.3800	420.08	0.2037
Mois*Rep(Wind)	6	205.08		206.53	
Cutting	3	63.42	0.0001	624.97	0.0001
Cut*Wind	3	3.64	0.3032	35.86	0.0194
Cut*Rep(Wind)	18	2.79		8.42	
Cut*Mois	3	1.42	0.8310	6.97	0.7189
Cut*Wind*Mois	3	3.42	0.5626	9.19	0.6255
Cut*Mois*Rep(Wind)	18	4.86		15.42	
Subsample Error	128				
Total	191				
C.V. (%)		11.8		13.4	

Table B.8. Analysis of variance for response of alfalfa stem density to treatments obtained over 4 cuttings during the 1984 and 1985 growing season.

Source of Variation	DF	1984 Mean Square	1984 P>F	1985 Mean Square	1985 P>F
Wind Condition	1	56033.33	0.2436	191268.75	0.0663
Replication(Wind)	6	33526.00		38110.97	
Moisture Regime	1	27075.00	0.1635	37968.75	0.1055
Mois*Wind	1	8427.00	0.4099	24934.08	0.1737
Mois*Rep(Wind)	6	10744.11		10466.97	
Cutting	3	350661.10	0.0001	126915.86	0.0001
Cut*Wind	3	25207.33	0.0357	378.97	0.9671
Cut*Rep(Wind)	18	7121.70		4434.23	
Cut*Mois	3	5087.67	0.3940	7711.86	0.0218
Cut*Wind*Mois	3	7798.33	0.2217	855.86	0.7158
Cut*Mois*Rep(Wind)	18	4838.19		1873.94	
Subsample Error	128				
Total	191				
C.V. (%)		8.8		9.4	

Table B.9. Analysis of variance for response of alfalfa stems per plant to treatments obtained over 4 cuttings during the 1984 and 1985 growing season.

Source of Variation	DF	1984 Mean Square	1984 P>F	1985 Mean Square	1985 P>F
Wind Condition	1	26.71	0.2879	4.66	0.6984
Replication(Wind)	6	19.65		28.17	
Moisture Regime	1	12.22	0.3862	0.38	0.8956
Mois*Wind	1	11.15	0.4065	0.01	0.9797
Mois*Rep(Wind)	6	14.00		20.48	
Cutting	3	129.28	0.0001	66.16	0.0001
Cut*Wind	3	9.64	0.0265	2.06	0.3985
Cut*Rep(Wind)	18	2.48		1.98	
Cut*Mois	3	1.37	0.5809	1.53	0.2831
Cut*Wind*Mois	3	4.14	0.1471	0.62	0.6485
Cut*Mois*Rep(Wind)	18	2.05		1.11	
Subsample Error	128				
Total	191				
C.V. (%)		18.7		21.6	

Table B.10. Analysis of variance for response of alfalfa dry matter yield to treatments obtained over 4 cuttings during the 1984 and 1985 growing season.

Source of Variation	DF	1984 Mean Square	1984 P>F	1985 Mean Square	1985 P>F
Wind Condition	1	1.01	0.3427	0.02	0.7568
Replication(Wind)	6	0.96		0.16	
Moisture Regime	1	3.58	0.0267	0.54	0.0482
Mois*Wind	1	1.23	0.1377	0.00	0.9647
Mois*Rep(Wind)	6	0.42		0.09	
Cutting	3	22.47	0.0001	65.65	0.0001
Cut*Wind	3	1.15	0.0360	0.33	0.0572
Cut*Rep(Wind)	18	0.33		0.11	
Cut*Mois	3	0.09	0.0001	0.14	0.3388
Cut*Wind*Mois	3	2.25	0.3688	0.15	0.3027
Cut*Mois*Rep(Wind)	18	0.08		0.12	
Subsample Error	128				
Total	191				
C.V. (%)		8.9		4.1	

Table B.11. Analysis of variance for response of alfalfa leaf crude protein to treatments obtained over 4 cuttings during the 1984 and 1985 growing season.

Source of Variation	DF	1984 Mean Square	1984 P>F	1985 Mean Square	1985 P>F
Wind Condition	1	10.06	0.2257	0.04	0.8516
Replication(Wind)	6	5.52		1.01	
Moisture Regime	1	11.23	0.0464	0.39	0.1508
Mois*Wind	1	7.02	0.0952	0.01	0.8023
Mois*Rep(Wind)	6	1.79		0.14	
Cutting	3	9.25	0.0513	18.87	0.0001
Cut*Wind	3	14.29	0.0122	0.15	0.8555
Cut*Rep(Wind)	18	2.95		0.60	
Cut*Mois	3	3.23	0.0498	0.16	0.3512
Cut*Wind*Mois	3	4.72	0.0143	0.27	0.1661
Cut*Mois*Rep(Wind)	18	1.02		0.14	
Subsample Error	128				
Total	191				
C.V. (%)		2.5		1.1	

Table B.12. Analysis of variance for response of alfalfa stem crude protein to treatments obtained over 4 cuttings during the 1984 and 1985 growing season.

		1984		1985	
Source of Variation	DF	Mean Square	P>F	Mean Square	P>F
Wind Condition	1	1.51	0.2288	0.04	0.8516
Replication(Wind)	6	0.84		1.01	
Moisture Regime	1	0.12	0.5955	0.39	0.1508
Mois*Wind	1	0.41	0.3450	0.01	0.8023
Mois*Rep(Wind)	6	0.39		0.14	
Cutting	3	33.04	0.0001	18.87	0.0001
Cut*Wind	3	2.45	0.0852	0.15	0.8555
Cut*Rep(Wind)	18	0.95		0.60	
Cut*Mois	3	0.18	0.8156	0.16	0.3512
Cut*Wind*Mois	3	1.66	0.0659	0.27	0.1661
Cut*Mois*Rep(Wind)	18	0.58		0.14	
Subsample Error	128				
Total	191				
C.V. (%)		2.9		1.8	

Table B.13. Analysis of variance for response of alfalfa whole plant crude protein to treatments obtained over 4 cuttings during the 1984 and 1985 growing season.

Source of Variation	DF	1984 Mean Square	1984 P>F	1985 Mean Square	1985 P>F
Wind Condition	1	6.75	0.1579	1.52	0.3898
Replication(Wind)	6	2.60		1.77	
Moisture Regime	1	0.13	0.7158	0.21	0.4877
Mois*Wind	1	1.13	0.3052	1.85	0.0704
Mois*Rep(Wind)	6	0.90		0.38	
Cutting	3	23.13	0.0001	94.45	0.0001
Cut*Wind	3	6.82	0.0163	1.06	0.2509
Cut*Rep(Wind)	18	1.52		0.71	
Cut*Mois	3	4.65	0.0119	0.73	0.0886
Cut*Wind*Mois	3	2.19	0.1122	0.75	0.0829
Cut*Mois*Rep(Wind)	18	0.96		0.29	
Subsample Error	128				
Total	191				
C.V. (%)		2.4		1.7	

Table B.14. Analysis of variance for response of alfalfa leaf IVDMD to treatments obtained over 4 cuttings during the 1984 and 1985 growing season.

		1984		1985	
Source of Variation	DF	Mean Square	P>F	Mean Square	P>F
Wind Condition	1	0.12	0.9581	10.98	0.1253
Replication(Wind)	6	39.09		3046	
Moisture Regime	1	0.20	0.8811	4.82	0.2771
Mois*Wind	1	13.75	0.2421	1.36	0.5488
Mois*Rep(Wind)	6	8.17		3.38	
Cutting	3	116.11	0.0001	126.24	0.0001
Cut*Wind	3	21.86	0.0180	4.42	0.3486
Cut*Rep(Wind)	18	5.02		3.77	
Cut*Mois	3	2.02	0.5617	1.10	0.4094
Cut*Wind*Mois	3	2.72	0.4395	2.91	0.0769
Cut*Mois*Rep(Wind)	18	2.87		1.08	
Subsample Error	128				
Total	191				
C.V. (%)		1.9		1.2	

Table B.15. Analysis of variance for response of alfalfa stem IVDMD to treatments obtained over 4 cuttings during the 1984 and 1985 growing season.

Source of Variation	DF	1984 Mean Square	1984 P>F	1985 Mean Square	1985 P>F
Wind Condition	1	0.03	0.9602	0.12	0.9354
Replication(Wind)	6	12.05		16.64	
Moisture Regime	1	7.48	0.2343	8.58	0.1202
Mois*Wind	1	0.11	0.8794	6.43	0.1679
Mois*Rep(Wind)	6	4.28		2.62	
Cutting	3	348.70	0.0001	850.63	0.0001
Cut*Wind	3	7.12	0.4419	4.42	0.7638
Cut*Rep(Wind)	18	7.57		11.42	
Cut*Mois	3	1.91	0.5919	0.44	0.8284
Cut*Wind*Mois	3	4.35	0.2514	7.09	0.0129
Cut*Mois*Rep(Wind)	18	2.93		1.49	
Subsample Error	128				
Total	191				
C.V. (%)		2.0		1.5	

Table B.16. Analysis of variance for response of alfalfa whole plant IVDMD to treatments obtained over 4 cuttings during the 1984 and 1985 growing season.

Source of Variation	DF	1984 Mean Square	1984 P>F	1985 Mean Square	1985 P>F
Wind Condition	1	6.75	0.1579	0.02	0.7568
Replication(Wind)	6	2.60		0.16	
Moisture Regime	1	0.13	0.7158	0.54	0.0482
Mois*Wind	1	1.13	0.3052	0.00	0.9647
Mois*Rep(Wind)	6	0.90		0.09	
Cutting	3	23.13	0.0001	65.65	0.0001
Cut*Wind	3	6.82	0.0163	0.33	0.0572
Cut*Rep(Wind)	18	1.52		0.11	
Cut*Mois	3	4.65	0.0119	0.14	0.3388
Cut*Wind*Mois	3	2.19	0.1122	0.15	0.3027
Cut*Mois*Rep(Wind)	18	0.96		0.12	
Subsample Error	128				
Total	191				
C.V. (%)		1.4		1.2	